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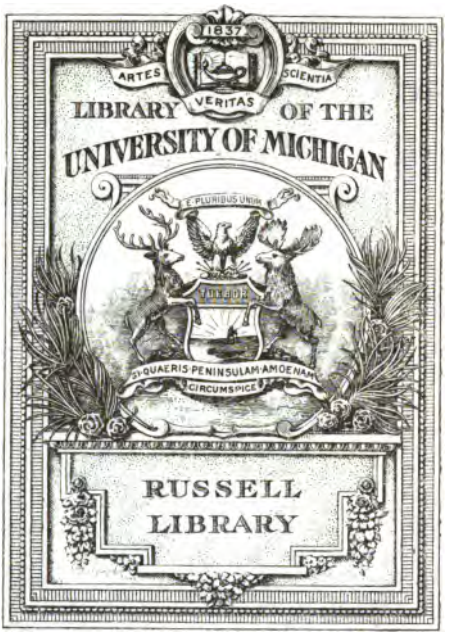

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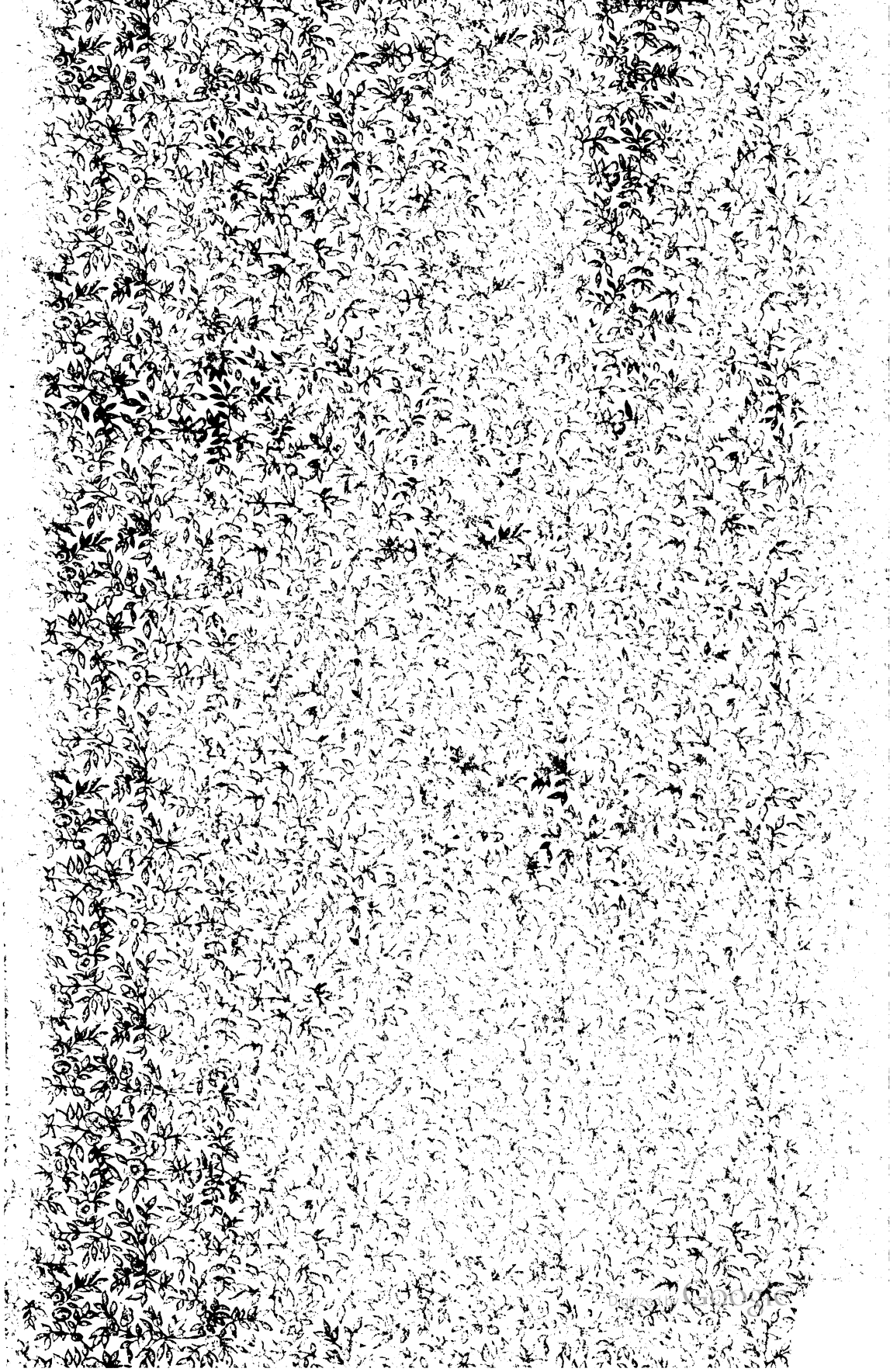

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MINERALS IN ROCK SECTIONS

Israel C. Russell

THE PRACTICAL METHODS

OF

IDENTIFYING MINERALS IN ROCK SECTIONS WITH THE MICROSCOPE.

ESPECIALLY ARRANGED FOR STUDENTS IN TECHNICAL AND SCIENTIFIC SCHOOLS.

BY

LEA McILVAINE LUQUER, C.E., PH.D.
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PREFACE.

The identification of minerals in rock sections with the microscope, including as it does a knowledge of optical mineralogy, is often difficult for beginners. This may be due to the fact that most of the publications on this subject are quite elaborate in their nature and in either French or German. While detailed descriptions are very necessary, and, in fact, indispensable for advanced investigation, they are apt to prove cumbersome and confusing at first. For these reasons this text-book has been prepared by the writer, with a view of putting before the student only those facts which are absolutely necessary for the proper recognition and identification of the common minerals in rock sections. The foot-notes refer the student to standard publications, in which are given details of the methods and investigations outlined in the text. An elementary knowledge of crystallography and mineralogy is almost indispensable and is here assumed.

The microscopic and optical characters of the minerals are recorded in the usual order in which they would be observed with a petrographical microscope. Nearly all the rock-forming minerals become transparent in thin sections; but when opaque, attention is called to the fact and the characters are recorded as seen with incident light. White light is assumed to be used, unless otherwise stated. The interference colors recorded in all cases are those given by very thin sections of 0.03 mm. in thickness.

The order followed for the minerals is essentially that of Rosenbusch (based on the symmetry of the crystalline form), with a few exceptions made for convenience, such as placing pyrrhotite after pyrite and zoisite after epidote. The statements regarding the occurrences of minerals in the common rock-types have been

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taken mainly from Les Minéraux des Roches, by Levy and Lacroix.

The terms axes and directions of elasticity, used throughout this book, are very commonly employed in petrographical literature of the present time. These axes and directions should probably more correctly be called axes and directions of vibration or extinction. The reasons for or against the elastic condition of the "ether" are of more interest, however, to the physicist than to the petrographer.

An optical scheme is appended, with the minerals grouped according to their common optical characters.

The writer's thanks are due to Dr. A. J. Moses, Professor of Mineralogy, and to Mr. J. F. Kemp, Professor of Geology, for kind suggestions offered during the preparation of this book.

L. McI. L.

DEPARTMENT OF MINERALOGY,
COLUMBIA UNIVERSITY, N. Y. CITY,
October, 1898.

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TABLE OF CONTENTS.

PAGE.

Conventions and Abbreviations. vii

Errata and Addenda.

P. 1, 1st foot-note. Add E. S. Dana's *Text-Book of Mineralogy*, last edit., 1898.

P. 8, 1st foot-note. Add 14th. ed.

P. 32, (a), 1st line. Read, slightly inclined for normal (when sections are normal the curves become nearly circular).

P. 97, 28th line. Read, intensity for moment.

Read, Iddings' Rosenbusch for Iddings' Translation, wherever found.

For a more complete discussion of the production of interference colors (p. 22) reference is made to A. J. Moses, *Characters of Crystals*, p. 106 et seq.

CHAPTER III.

Investigation of Microscopic and Optical Characters of Minerals.

Opaque Minerals.

Transparent Minerals:

With transmitted light; *Form*, *Color*, *Relief*, *Cleavage*, *Fracture*, *Inclusions*.

With polarized transmitted light; *Pleochroism*, *Absorption*.

With crossed nicols: *Isotropic Character*, *Anisotropic Character*, *Double Refraction* and *Interference Colors*, *Extinction* and *Extinction Angles*, *Structure*.

With convergent light; *Uniaxial Interference Figures* and *Optical Character*, *Biaxial Interference Figures* and *Optical Character*.

Resumé of Uses of Parallel and Convergent Light, ... 11

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CHAPTER IV.

Microscopic and Optical Characters of Minerals.

Amorphous Minerals.—Isometric Minerals.—Tetragonal Minerals.—Hexagonal Minerals.—Orthorhombic Minerals.—Monoclinic Minerals.—Triclinic Minerals.—Mineral Aggregates, ... 35

CHAPTER V.

Methods of Preparing Sections.

Cutting and Grinding Machines.—Saws.—Cutting.—Grinding Plates or Laps.—Cementing.—Grinding.—Mounting.—Cleaning and Finishing.—Convenient Apparatus for Work, ... 81

CHAPTER VI.

Chemical and Mechanical Tests.

Chemical Tests on Crystal in Section; *Carbonates, Gelatinizing Silica.*—Etched Figures.—Heating Sections to Redness.—Methods of Isolating Crystals or Fragments for Testing; *Specific Gravity Separation, Electro-magnetic Separation, Chemical Separation.*—Micro-Chemical Reactions; *Borichy's Method, Behren's Method, Special Tests*, ... 92

APPENDIX.

Brief Scheme of Classification into Systems by Optical Determinations.—Measuring Strength of Double Refraction.—Order of Consolidation of the Constituent Minerals in Plutonic Rocks.—Newton's Color-Scale.—Optical Scheme with Special Introduction, ... 103

Index, ... 113

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CONVENTIONS AND ABBREVIATIONS.

ELONGATION = The general direction of greatest extension that a crystal may exhibit in a rock section. In crystals of long prismatic habit marked elongation would show that the section was taken approximately parallel to the vertical or prism axis; while in crystals of tabular habit (the micas) elongation would indicate that the section was approximately at right angles to the tabular faces (the basal faces in micas). At times, of course, no elongation is appreciable, as in the case of granular or broken crystals or where the cross-section is essentially square or octagonal. Very often the relation of the cleavage is given to the elongation and the directions a' and c', which makes it possible to test for a' and c' even when no marked elongation can be observed.

a' = A direction of maximum elasticity,* which need not necessarily be the axis of maximum elasticity.

c' = A direction of minimum elasticity, which need not necessarily be the axis of minimum elasticity.

(+) = Optical character positive.

(−) = Optical character negative.

$\|$ = Parallel to.

$(\gamma - \alpha)$ = The difference between the indices of refraction of the two rays with ether vibrations parallel to the axes of minimum and maximum elasticity respectively, and indicates in decimals the relative strength of the double refraction.

n' = The mean index of refraction; hence

$$= \frac{\alpha + \beta + \gamma}{3} \text{ or } \frac{\epsilon + 2\omega}{3}.$$

a, b and c relate to the crystallographic axes commonly represented by these letters.

IDDINGS' ROSENBUSCH = Iddings' translation of Mikroskopische Physiographie der petrographisch wichtigen Mineralien, von Rosenbusch.

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* Or the assumed direction of the ether vibrations of the faster ray. The assumed direction of the ether vibrations of the slower ray is c'.

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MINERALS IN ROCK SECTIONS.

CHAPTER I.

INTRODUCTORY OPTICS FOR OPTICAL MINERALOGY.

As the object of this introduction is merely to give a practical, elementary knowledge of optics, as applied to optical mineralogy,* no elaborate discussion of this important subject will be attempted. The explanations will be made as simple as possible, and, in most cases, only the optical phenomena will be described without entering into a theoretical discussion as to the cause of these phenomena.

Light is transmitted by vibrations, of the "luminiferous ether," taking place at right angles to the direction of transmission.

Ordinary light is light with the ether vibrations in all possible directions, the path described by any particle of ether constantly changing.

Plane polarized light is simply light with the ether vibrations all *parallel* to one plane.

By experiments it has been proved that there exists a very close relation between the optical properties of crystals and their other physical properties, such as form, color, transmission of heat, etc. Therefore it is often possible, by a careful optical investigation of a crystal section, to determine important crystallographic facts, even in the absence of any distinct outline.

The Effects Produced by Crystals on Transmitted Light.

Consider that a series of optical tests are made on all possible sections † of crystals in the six systems, and the manner in which these crystals affect transmitted light ascertained.

* For a more complete discussion of optics, in connection with Optical Mineralogy, the student is referred to A. J. Moses' *Characters of Crystals*, p. 85, et seq.; Groth's *Physikalische Krystallographie*, 3d edit; Rosenbusch's *Mikroskopische Physiographie*, 3d edit.; and Iddings' *Translation of Rosenbusch*, 2d edit.

† These sections are supposed to have plane parallel faces, such being the case in ordinary practice, and to be examined with parallel incident light.

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In some crystals a *single image* of a point is seen through any section, and it has been proved that in these the light advances with equal velocity in all directions; that is, the crystals are optically equivalent in all directions. This is the case with *Isometric* crystals,* and in these crystals any section, however cut, will transmit all the parallel incident rays of light with no change.† The same is true of *Amorphous* bodies, glass, etc., unless they have been subjected to strains or peculiar conditions during cooling.

All such crystals are called optically **Isotropic.**

It has also been found that sections of some crystals have the property of showing a *double image* of a point. Calcite, especially the variety Iceland spar, exhibits this phenomenon very beautifully.

This is called *double refraction*,‡ and seems to be due to the power of resolving the ether vibrations of a ray of light into two sets of vibrations, taking place parallel to planes at right angles to each other,§ the two resulting rays traversing divergent paths in the section.

The velocity of transmission of light varies in different directions in these crystals, proved by the different values of the indices of refraction obtained by measurement.

Of course, it is only possible to make this test for double refraction, *i. e.*, the seeing of a double image, with thick crystal sections which have very strong double refraction like calcite. It is convenient, however, to think of double refraction as producing this effect. In most cases the separation of the two images is so slight as not to be perceived by the eye, and the practical method of testing a substance for double refraction will be given later, see p. 20.

All crystals in which the velocity of transmission of light is dependent on the direction and which produce double refraction, transmitting rays of light with ether vibrations in two planes at right angles to each other, are called optically **Anisotropic.**

To this class belong all crystals except those of the *Isometric* system.

* It is interesting to remember in this connection that in the isometric system there is also the greatest possible symmetry of "form."

† A. J. Moses, *Characters of Crystals*, pp. 85–97.

‡ For this branch of optical physics see A. J. Moses, *Characters of Crystals*, pp. 97–100.

§ This can easily be demonstrated by using a nicol and a plate of calcite which shows a double image. If the nicol is held between the calcite plate and the observer's eye it can be so adjusted that only one image is seen. If now the nicol is revolved 90° the first image will disappear and the other image alone will be seen.

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The crystals which show double refraction are further divided into two groups:

1°. *Uniaxial*, or those that have one direction parallel to which there is no double refraction.* To this group belong all *Tetragonal* and *Hexagonal* crystals.

2°. *Biaxial*, or those that have two directions parallel to which there is no double refraction. To this group belong all *Orthorhombic*, *Monoclinic* and *Triclinic* crystals.

The direction parallel to which there is no double refraction is called an **Optic Axis.**†

The directions, at right angles to each other, parallel to which the ether vibrations take place of the rays of light passing through a section of a doubly-refracting substance may be called **Directions of Elasticity‡ or Vibration.**

The directions of vibration (found always to be at right angles to each other) of the rays which advance with maximum and minimum§ velocity and a third direction at right angles to the plane of these directions (corresponding to some ray with an intermediate velocity) are called **Axes of Elasticity or Principal Vibration Directions.**

In *Uniaxial* crystals the optic axis coincides with the vertical axis $\dot{c}$, which is also an axis of either maximum or minimum elasticity. The optical behavior is symmetrical to $\dot{c}$, and hence is the same for all directions equally inclined to $\dot{c}$. The other axes of elasticity, being equally inclined (90°) to $\dot{c}$, are equal and their absolute positions indifferent.

It will readily be seen that any section parallel to the base, be-

* In some cases a peculiar form of double refraction does take place parallel to this direction, as in the circular polarization of quartz and cinnabar; but in very thin sections these results are not noticed and can be disregarded.

† In biaxial crystals the directions called optic axes are not strictly speaking axes, because they change their position, to a greater or less extent, for light of different wave-length. For most cases, however, in observations with white light the optic axes may be regarded as approximately fixed in position.

‡ The term *elasticity* is merely used for convenience in order to bring this text-book into conformity with most of the books on petrography published at the present time, by Zirkel, Rosenbusch, Harker, Hatch, etc. Lévy and Lacroix do not use the expression. Groth, in his Physikalische Krystallographie, III Ed., treats of the subject without discussing the question of elasticity. Liebisch does not consider the ether as elastic. Fletcher regards the theory of the ether being elastic as untenable from a mathematical standpoint.

§ Proved by determining the indices of refraction of the rays with ether vibrations parallel to these axes.

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ing at right angles to an optic axis, acts like a section of an isotropic crystal, and transmits all the parallel incident rays of light with no change. Any section parallel to the vertical axis $\dot{c}$ contains two axes of elasticity and is therefore called an *optical principal section;* and of the two rays of light, that with ether vibrations parallel to the basal plane is called the *ordinary ray O*, the other ray being called the *extraordinary ray E.** The index of refraction of O is denoted by ω and that of E by ε.† Any other section contains two directions of elasticity, always at right angles to each other; one direction being the trace of the plane, passing through the incident ray and the vertical axis $\dot{c}$ of the crystal, on the plane of the section; the other direction being at right angles to this.

In *Biaxial* crystals the three axes of elasticity, at right angles to each other, are denoted by $\mathfrak{a}$ = maximum, $\mathfrak{b}$ = intermediate, and $\mathfrak{c}$ = minimum. These axes of elasticity are the intersections of the three planes, towards which the optical behavior is symmetrical. Each plane contains two axes of elasticity and, as in the uniaxial crystals, is called an *optical principal section.* The index of refraction of the ray with ether vibrations parallel to $\mathfrak{a}$ is denoted by α, that of the ray with ether vibrations parallel to $\mathfrak{b}$ by β, and that of the ray with ether vibrations parallel to $\mathfrak{c}$ by γ.‡

In the *Orthorhombic* system the axes of elasticity coincide with the crystallographic axes.

In the *Monoclinic* system one axis of elasticity coincides with the ortho axis $\bar{b}$, the other two axes of elasticity are in the plane of symmetry§ normal to the axis $\bar{b}$, but do not coincide with either the vertical axis $\dot{c}$ or the clino axis $\dot{a}$. The relative positions of these axes will be best understood by the accompanying figures. Fig. 1. represents a section parallel to the clinopinacoid, $\infty\breve{P}\infty$ (010). The axes of elasticity are denoted by dotted lines, and the crystal-

* See A. J. Moses, *Characters of Crystals*, pp. 98, 99.

† Instead of ω and ε, for conveniences in tables, etc., α and γ are used, denoting the indices of refraction of the rays traversing the crystal with greatest and least velocity respectively, without regard as to which is the O or E ray. A good reason for this convention is that the symbol $(\gamma - \alpha)$ is used to express in decimals the relative strength of the double refraction of a crystal, whether uniaxial or biaxial. γ is always greater than α.

‡ The ray with ether vibrations parallel to $\mathfrak{a}$ advances with greatest velocity, the $\mathfrak{c}$ ray with least velocity and the $\mathfrak{b}$ ray with some intermediate velocity.

§ A. J. Moses, *Characters of Crystals*, p. 132.

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lographic axes by solid lines. The ortho axis $\bar{b}$ and the remaining axis of elasticity are normal to the pinacoid plane.

The angles $x\ o\ \dot{c}$ and $\dot{c}\ o\ y$ are called extinction angles, and vary with different species, being very characteristic of some minerals such as amphibole and pyroxene.

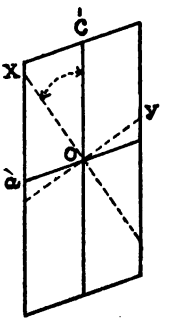

FIG. 1.

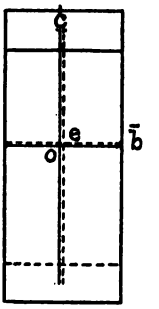

FIG. 2.

Consider now an orthopinacoid section, $\infty P\bar{\infty}$ (100). In Fig. 2 $o\ \bar{b}$ is the ortho axis $\bar{b}$, $o\dot{c}$ the vertical axis $\dot{c}$, $e\bar{b}$ an axis of elasticity parallel to $\bar{b}$ and $e\ \dot{c}$ a direction of elasticity to parallel $\dot{c}$. The direction $e\ \dot{c}$ is not an axis of elasticity, because the elasticity (or the optical condition affecting the transmission of light) in that direction is intermediate in value between the two values of the axes of elasticity lying in the plane normal to $\bar{b}$. There is no extinction angle in an orthopinacoid section. The same is true of a basal section and of all sections in the ortho zone* $0P : \infty P\bar{\infty}$ (001 : 100). We see that for sections in the prism zone $\infty P\breve{\infty} : \infty P\bar{\infty}$ (010 : 100), *i. e.*, parallel to the vertical axis, the extinction angles will vary from 0°, when the section is parallel to the orthopinacoid, to a maximum value when the section is parallel to the clinopinacoid.

In the *Triclinic* system no axis of elasticity is parallel to a crystallographic axis, and there is no definite relation between the axes of elasticity and the crystallographic axes; hence in all possible sections there will be extinction angles. It must be remembered, however, that there is still symmetry in the optical conditions to the three planes already mentioned.

* A preliminary knowledge of crystallography and zones is here assumed. See Moses and Parsons, *Mineralogy, Crystallography and B. P. Analysis*, and E. S. Dana, *Text Book of Mineralogy*, New Ed., 1898, p. 26.

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In all *biaxial* crystals the two *optic axes* are inclined to each other, making what is called the *axial angle*,* denoted by $2E$. This angle is really the apparent angle measured in air, $2V$ being the true axial angle.† The optic axes always lie in the plane of the axes of maximum and minimum elasticity, and the angles between them are always bisected by these axes of elasticity. The axis of elasticity bisecting the acute axial angle is called the *acute bisectrix*. An approximate idea of the value of the axial angle can be obtained by the use of the petrographical microscope, as described later, p. 33. The axial angle is often a convenient differentiation between such minerals as muscovite and biotite.

The axial angle will vary with light of different wave-length or color, and this variation is called *dispersion* of the optic axes. Dispersion of the axes of elasticity also takes place in monoclinic and triclinic crystals, but can be disregarded in ordinary investigations.

The location of the optic axis or axes is necessary when the uniaxial or biaxial nature or the optical character is required, and the determination of the axes or directions of elasticity and their relative values is also generally essential.

In closing it is very important to remember that any section of an anisotropic crystal (not normal to an optic axis) will always transmit rays of light with ether vibrations in two planes at right angles to each other, the two sets of rays, however, following divergent paths in the section. Hence all such sections have two directions of elasticity at right angles to each other. Isometric crystal sections, of course, produce no double refraction.

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* For methods of measuring the axial angle, see A. J. Moses, *Characters of Crystals*, Chap. XI., pp. 148–153.

† For convenience in many cases only $2E$ is recorded, as then an indication is given as to whether the axial angle is visible with an ordinary microscope (arranged for observation with convergent light for interference figures). If $2E$ is very large the axial angle can only be observed by covering the section with some transparent, strongly refracting fluid. For the Seibert microscope with objective V the limit for good results is about $2E = 90°–100°$.

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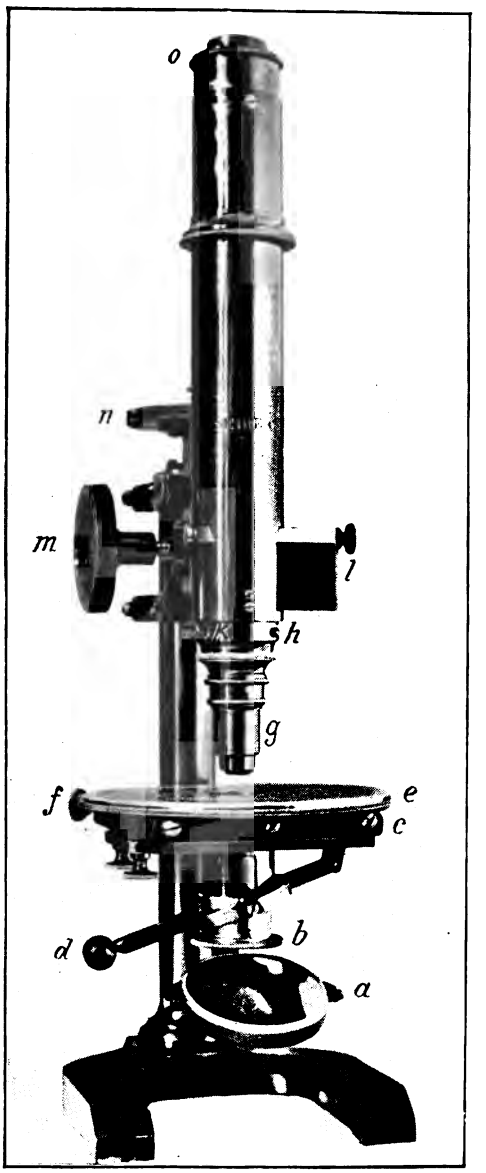

FIG. 3.

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CHAPTER II.

The Petrographical Microscope. *

The *petrographical microscope* is essentially an ordinary microscope † with the following important additional equipment. It must be provided with: 1° a *polarizer* (a piece of apparatus for giving polarized light) placed below the stage; 2° an *analyzer* (a piece of apparatus for analyzing the rays of light after they have passed through the polarizer and transparent section) placed between the objective and the eye; 3° a *stage rotating* about an axis which is the line of sight of the microscope. A very convenient type of microscope is that made by Seibert of Wetzlar (No. 11 *a*), Fig. 3.

The *reflector a* is usually fitted with a plane mirror on one side, and a parabolic mirror on the other. The plane mirror should be used with sunlight, and the parabolic mirror with artificial light, in order to make the rays of light as nearly parallel as possible.

The *polarizer* is in most cases a nicol prism, set in a suitable frame *b*, and made as follows:

For the *nicol prism* "a cleavage rhombohedron of calcite (the variety Iceland spar is universally used in consequence of its transparency) is obtained, having four large and two small rhombohedral faces opposite each other. In place of the latter planes, two new surfaces are cut, making angles of 68° (instead of 71°) with the obtuse vertical edges; these then form the terminal faces

* For a short historical sketch of the use of the microscope in connection with Petrology, see G. H. William's pamphlet, *Modern Petrography* (*Monographs of Education*), Boston, 1886.

† For description of the ordinary microscope, eye-pieces, objectives, magnification, etc., see *Manipulation of the Microscope*, by Ed. Bausch.

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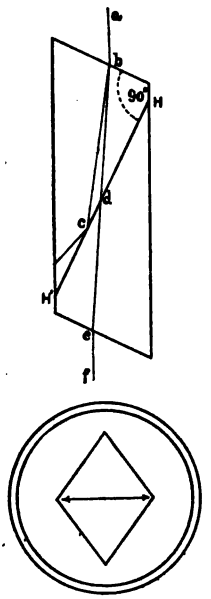

FIG. 4.

of the prism. In addition to this, the prism is cut through in the direction HH′, Fig. 4, the parts then polished and cemented together again with Canada balsam. A ray of light, *ab*, entering the prism, is divided into two rays polarized at right angles to each other. One of these, *bc*, on meeting the layer of balsam (whose refractive index is less than that of the ray *bc*), suffers total reflection, and is deflected against the blackened sides of the prism and extinguished. The other, *bd*, passes through and emerges at *e*, a completely polarized ray of light, that is, a ray with vibrations in one direction only, and that the direction of the shorter diagonal of the prism." * The vertical plane through the shorter diagonal may be called the *plane* of *vibration*† of the nicol.

The polarizer must be below the stage *c*, and is generally adjusted so as to have its plane of vibration parallel to the N. and S. cross-wire in the eye-piece *o*. It is important to know the direction of the plane of vibration of the polarizer or lower nicol; as we can then determine, when absorption of light occurs in a mineral, the direction in this mineral parallel to which the absorbed rays are vibrating. The polarizer slides in an outer shell or frame, and, by means of a lever *d*, can easily be raised or lowered.

On the top of the nicol is placed the *condensing lens* for getting *convergent* light, and the adjustments are so arranged that when the nicol is up as far as it will go, the condensing lens ‡ is brought almost in contact with the lower surface of the transparent section resting on the stage.

The *rotating* circular *stage*, *e*, is supported on a suitable frame *c*, and arranged so that its axis of rotation coincides with the line of sight of the microscope. The stage is graduated, and, by means of an index fixed to the frame, the angular rotation can always be

* Text Book of Mineralogy, by E. S. Dana, p. 133.

† It is convenient to assume that the vibrations of the polarized light are taking place in this plane, called the "plane of vibration," but all the phenomena caused by polarized light could be also explained on the assumption that the vibrations were taking place at right angles to this plane.

‡ This condensing lens must be removed when very low power objectives are used.

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obtained. It is also provided with two adjusting screws* *f* by means of which the axis of rotation can be accurately centered.

The method of centering is as follows: Bring some prominent mark in the section exactly in coincidence with the intersection of the cross-wires in the eye-piece. Rotate the stage 180°, and correct one-half the error by means of the centering screws, and the other half by moving the section on the stage. Check the result by rotating the stage 180° again, and if necessary make the corrections in the same way until the adjustment is satisfactory.

The *objective*† *g* screws into the collar *h*, which has a slot *k*, in the upper portion, for the introduction of a sensitive color plate, a ¼ undulation mica plate or a quartz wedge.‡

The slot *k*, is usually so arranged that, when the sensitive color plates are introduced, the axes of these plates will make an angle of 45° with the planes of vibration of the crossed nicols, and the interference color produced will thus be at its maximum intensity.

A revolving *nose-piece* is sometimes used which can be attached to the collar *h*, and which is arranged to carry two or three objectives, which can thus be very quickly brought into position for use. This is convenient in passing rapidly from observations with parallel light to observations with convergent light, which must be made with a high power objective. The difficulty is that recentering is generally required.

The *analyser*§ or upper nicol is contained in the frame *l*, which is arranged so as to slide in and out of the tube of the microscope.

The plane of vibration of the analyser is generally fixed by the instrument maker so as to be parallel to the E. and W. cross-wire in the eye-piece. Consequently when the frame *l* is pushed into

* Some microscopes are provided with adjusting screws bearing on the frame holding the objective, which can then be accurately centered to the axis of rotation of the stage.

† In the Seibert Microscope use objective No. 00 for the first general study of a rock section, No. II for general use and No. V for observations with convergent light. In the case of an English Microscope a 1″ to ¾″ objective is used for general purposes and a ¼″ to ⅛″ for observations with convergent light.

‡ See Iddings Translation, p. 63, for description of quartz plate; p. 65, for quartz wedge; and p. 81 for ¼ undulation mica plate.

§ In some microscopes the analyser is in the form of a "cap" nicol, arranged to be fitted over the top of the eye-piece, and not introduced in the microscope tube as shown here. This form is not so convenient, as the "cap" nicol must be set by hand every time it is desired to make observations with crossed nicols. But at the same time it avoids any possible refocusing which may be necessary when the other type of analyser is introduced in the tube.

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the tube, the analyser is introduced in the line of sight between the objective and the observer's eye, with its plane of vibration at right angles to the plane of vibration of the polarizer; that is the nicols are crossed. When the nicols are crossed, if they are properly adjusted, no light can pass through to the eye and the field of view should be dark.

The *eye-piece** *o*, fits into the top of the tube, and, by means of a little projecting piece fitting into a slot in the frame, can always be adjusted so as to have its cross-wires parallel to the planes of vibration of the two nicols.

Some instruments are provided with an additional slot in the tube between the analyser and the eye-piece for the introduction of a Bertrand lens, which is used to magnify the interference figures produced by convergent light.

The first approximate focusing is made by the screw *m*, and the fine adjustment by the screw *n*.

In focusing always start with the objective very near the section, and move it away until the right focus is obtained. Never move down towards the section in obtaining the focus, as there is danger then of striking the objective against the section.

* In the Seibert microscope eye-piece No. 0, is used for most purposes. Other eye-pieces, Nos. I and III, with cross-wires, are used for different degrees of magnification, and one eye-piece No. II, without cross-wires, is provided to be used in connection with an eye-piece micrometer. Eye-pieces with cross-wires and different degrees of magnification are also provided with the English microscopes.

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CHAPTER III.

Investigation of Microscopic And Optical Characters of Minerals.

Characters of Opaque Minerals, observed by *incident* light. The minerals which remain perfectly opaque in thin rock sections have usually metallic lustre and are very minute in size, as is the case with the iron ores.

When the metallic minerals of a rock specimen are distinctly seen with the unaided eye, it is rarely necessary to make a section for their determination, as this can more easily be done by any of the well known blowpipe methods.

Form, Lustre, Color, Cleavage, etc., are recognized in the same way as in the case of macroscopic specimens. In order to make the observations by incident light alone, the beam of light from the reflector-mirror must be cut off by holding the hand over the mirror or by moving the mirror.

Characters of Transparent Minerals, observed by *transmitted* light. The petrographical microscope for these observations is supposed to be in the condition of an ordinary microscope, both nicols being out of the field and a strong beam of light coming up through the transparent section from the reflector below.

The characters are considered in the order in which they would most naturally appear to the observer during a complete investigation with the microscope.*

(a). **Form.**† *Complete Crystals*, with definite crystalline outline, *i. e.*, crystals that have formed when conditions were favorable for complete development. Such crystals are often called *Idiomorphic*,

* With the Seibert microscope, Fig. 3, the No. 0 eye-piece and the No. II. objective will prove most satisfactory for the following tests. With an English microscope use an ordinary eye-piece and a 1″ or ¾″ objective.

† Twins may be recognized just as in macroscopic specimens, and zonal structure noticed if the zones differ in color. When a colorless mineral is surrounded by other colorless minerals, of about the same index of refraction, its outline is often best brought out by observation between crossed nicols.

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see Fig. 5. Crystals that are large in comparison with other accompanying crystals may be called *Phenochrysts*. In some cases,

FIG. 5.—Idiomorphic augite crystal in camptonite. The section is about at right angles to the vertical axis c, and shows the intersecting cleavages parallel to the prism of 87° 06′. Keene Valley, N. Y.

by a careful study of the outline of several sections of the same mineral and by a measurement of the angles, it is possible to determine the common crystallographic form of the mineral. For measuring the angles have the stage accurately centered, then bring

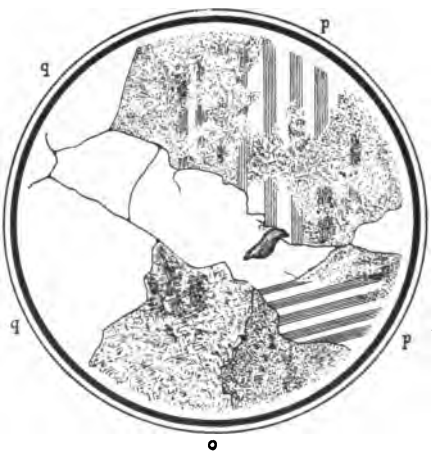

FIG. 6.—Allotriomorphic quartz q, showing "low relief," plagioclase p and decomposed feldspar o in granite. As seen with crossed nicols.

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the vertex of the angle to be measured to the intersection of the cross-wires in the eye-piece. Bring one of the sides in coincidence with one of the cross-wires. Note the reading of the graduated circle and rotate the section until the other side is in coincidence with the same wire. Take the reading again and the difference will be the angle required.

Incomplete Crystals, without definite crystalline outline, whose bounding surfaces are more or less determined by those of adjacent crystals. Such crystals are frequently called *Allotriomorphic*,* see Fig. 6. This allotriomorphic form must not be confounded with the worn or rounded boundaries of the component grains in clastic rocks.

Corroded Crystals,† whose fretted outline is undoubtedly due to corrosive action of the magma before solidification, see Fig. 7.

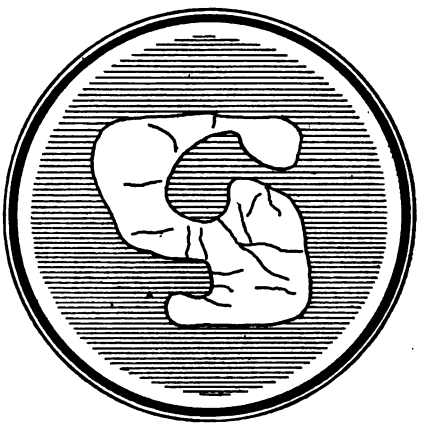

FIG. 7.—Corroded sanidine crystal in perlite.

Broken or Strained Crystals. In some cases what were formerly larger individuals have been broken or shattered by dynamic action to much smaller fragments, see Fig. 8, showing crushed rim of fragments surrounding feldspar "auge." In other cases an actual bending or distortion of the crystal has taken place, and again sometimes the effect of mechanical stress is only shown by the so called "wavy" extinction. See p. 24 and Fig. 8, showing

* The term "Anhedron," meaning without planes, has been suggested by L. V. Pirsson to describe in rocks the crystal fragments which have no plane faces, as, for example, the augites of augitic rocks, *Science*, Jan. 10, 1896, p. 49.

† Partial resorption and recrystallization may produce a border of secondary minerals, surrounding the original crystal.

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FIG. 8.—Orthoclase "auge" (Carlsbad twin), showing bending and "wavy" extinction, surrounded by crushed rim of mineral fragments. As seen with crossed nicols. "Augen"-gneiss, Bedford, N. Y.—B. 13.

a carlsbad twin of feldspar that has been bent and at the same time shows marked "wavy" extinction.

Crystallites, in general those incipient forms of crystals, which have not yet reached a stage of development sufficient to show double refraction, see Fig. 9, *a*. Quite a number of names are used to describe the different forms that occur.

FIG. 9.—Crystallites and Microlites *a*. Skeleton Crystals *b*.

Microlites, more or less completely defined microscopic crystals, which usually show double refraction, but cannot be always specifically determined, see Fig. 9, *a*.

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Skeleton Crystals or crystallizations which have not produced entire and complete individuals, see Fig. 9, *b*.

(b). **Color.** It must be remembered that the colors observed are always due to transmitted light and may be called "*absorption tints*." Minerals which in hand specimens are opaque, are often colored in sections; and minerals which are commonly colored may appear colorless in sections. At times color may be given to a section simply by the presence of a great number of inclusions.

(c). **Relief.** The appearance of the surface and outline of a mineral, dependent on the strength of its refractive index,

$$n = \frac{\sin i}{\sin r}.$$

High numbers indicate strong refraction and *vice versa*. In the case of uniaxial and biaxial minerals the mean value of the indices of refraction is used.

FIG. 10.—Olivine crystal in basalt showing "high relief" and cleavage.

A mineral which has *weak refraction* appears to have what is called *low relief*, *i. e.*, no dark contours and a smooth surface, see Fig. 6.

A mineral which has *strong refraction* appears to have *high relief*, *i. e.*, distinct dark contours and a rough or "shagreened" surface,*

* The surfaces of all minerals in sections are more or less rough, but this roughness is only made visible when there is a marked difference between the indices of refraction of the minerals, and the index of refraction of the balsam in which the minerals are embedded. The index of refraction of balsam is about 1.5, so it is only when the mineral has a high index of refraction that its surface appears rough. When internal structure is to be studied, the crystal should be surrounded by a fluid of nearly the same index of refraction as that of the crystal, and when the exterior of the crystal is to be studied then a fluid should be used with a very different index of refraction.

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which has bright illumination and appears to stand out above the surfaces of the surrounding minerals with weaker refraction, see Fig. 10.

The practical way of testing for the *relief* of a mineral is to make use of the lens for convergent light, which is placed on top of the lower nicol immediately below the section.

By lowering * the lens the high relief of a mineral section is made very apparent.

FIG. 11.—Biotite, showing perfect cleavage and "low relief," in rhyolite. A fragment of a sanidine crystal is seen at *s*.

(d). **Cleavage,** which appears as more or less distinct and regular lines or cracks, see Figs. 11 and 12.

These cleavage cracks may be parallel or intersect, depending on the position of the section relative to the cleavage planes of the crystal.

Cleavage is sometimes best observed by slightly lowering the condensing lens under the section. Crystals that have two good cleavages often develop so that the direction of elongation is par-

* The Seibert microscope has a very convenient and quick lowering adjustment, by means of the lever *d*, for making this test rapidly. For convenience the lower nicol and condensing lens are generally left in place below the stage of the microscope, as polarized light serves as well for these investigations as ordinary light. An additional advantage in this arrangement is that the condensing lens is always ready for the "relief" test and the lower nicol for the pleochroism test; but it must be remembered that the polarizer or lower nicol cuts out one-half of the light, which comes to it from the reflector, and this loss is important when high power objectives are to be used. When very low power objectives are used the condensing lens must also be removed.

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allel to the intersection of the two cleavages, while in the case of crystals with one good cleavage the tendency seems to be towards a tabular habit parallel to the cleavage. When sections show in-

FIG. 12.—Augite *a*, showing good cleavage, and plagioclase *p* in diabase. The plagioclase shows "polysynthetic" twinning between crossed nicols.

tersecting cleavage cracks it is often possible to easily recognize the mineral by its known cleavage angle, as in the case of amphibole and pyroxene.

(e). **Fracture**, which appears as irregular and non-parallel cracks, see Fig. 13.

FIG. 13.—Garnet in mica schist, showing fracture and "high relief." Franconia N. Y.

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(f). **Inclusions,** which may be *solid* (either distinct crystals or glass), *fluid* or *gas*, see Fig. 14. These inclusions are differentiated

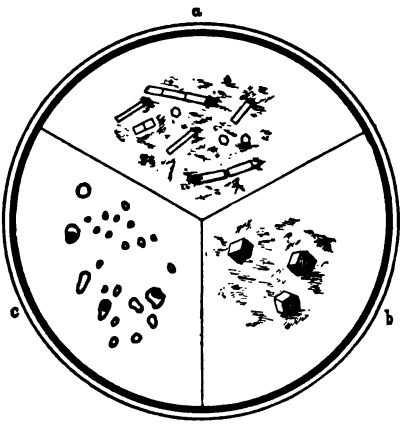

FIG. 14.—Apatite in feldspar *a*. Garnets in quartz, Branchville, Ct. *b*. Liquid inclusions of CO_2, some showing gas bubbles, in quartz *c*.

by the fact that the solid inclusions generally have sharp contours, the fluid inclusions distinct dark borders, and the gas inclusions broad dark borders more distinctly marked than those of the fluid inclusions. The fluid inclusions often contain a bubble of gas. The inclusions may have a definite or indefinite position in the crystal in which they occur, and can sometimes be more distinctly seen by using convergent light or a "spot" lens.

(g). **Schiller Structure.** "Is that in which cavities of definite form and orientation ('negative crystals') are developed along certain planes and filled or partially filled by material dissolved out of the enclosing crystal,"* see Fig. 15.

Characters Observed by Polarized or Parallel Transmitted Light.

The polarized light is obtained by passing the beam of light from the reflector through the polarizer or lower nicol,† which must be in place below the stage of the microscope.

* Harker's *Petrology for Students*, p. 280.

† The lower nicol is generally so adjusted that its plane of vibration is parallel to the north and south cross-wire in the eye-piece. This adjustment can be tested by means of a section of biotite, showing cleavage cracks. When the plane of vibration of the polarizer is parallel to the N. and S. cross-wire in the eye-piece, the biotite section becomes almost dark when its cleavage cracks are parallel to the same cross-wire. The upper nicol, or analyzer, must, of course, be removed during this test. This method is more convenient than taking the nicol out of its frame, in order to ascertain its plane of vibration (the direction of its shorter diagonal).

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(a). **Pleochroism,** that property which all anisotropic minerals have, to a greater or less extent, of absorbing certain colored rays in certain directions, thereby showing different colors in different directions by transmitted light. Uniaxial minerals are dichroic showing two differences in color, produced by the rays which vibrate parallel to the direction of the vertical axis *c* and the plane of the basal axes. Biaxial crystals are trichroic showing theoretically three differences of color, corresponding very nearly to the directions of the three axes of elasticity. Any given section of a biaxial crystal will, of course, appear only dichroic.

FIG. 15.—Hypersthene showing "Schiller" structure.

The practical way of testing for *pleochroism* is as follows: Revolve the stage, carrying the section, when a change in the color of the mineral will be noticed, if it is pleochroic. This pleochroism may appear as an actual change in color or simply as a change in the shade of the same color. In some cases it may be so weak as hardly to be noticed, when it is best to make the test with the condensing lens in position immediately under the section, or by rotating the lower nicol instead of revolving the stage. The color of the light, vibrating parallel to certain definite crystallographic directions in minerals, is often very characteristic.

Pleochroism may often be noticed with ordinary light in the case of hand specimens.

(b). **Absorption,** that property which some minerals have of absorbing all or nearly all of the light in certain directions. The change is one of intensity of light rather than of color, and is

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tested for in the same way as for pleochroism. If the absorption is strong, the crystal changes from its usual color to almost a black, and the interference colors may be masked. Strong absorption is characteristic of certain minerals, such as biotite, amphibole and tourmaline, and takes place parallel to definite directions in these minerals.

Characters Observed with both Polarizer and Analyzer* in Position, that is with "Crossed Nicols."

When the nicols are accurately crossed, the field should be quite dark, and if this is not the case the adjustments must be looked to. The condensing lens should be removed for these tests as they are to be made with parallel light, but as a matter of convenience instead of removing the condensing lens, the polarizer with the lens on top may be lowered, when the results will be about the same as with parallel light.

Isotropic Character. Sections of isotropic crystals are perfectly dark and remain so during a complete rotation of the stage through 360°. The explanation is very simple. Light being transmitted by an isotropic crystal in all directions without double refraction; it follows that the light from the polarizer, after having passed through the section, comes to the analyzer still vibrating in the plane of vibration of the polarizer. Hence it is entirely cut out by the analyzer.

Amphorous transparent substances act in the same way and remain dark during complete rotation of the stage.

Optical anomalies, i. e., apparent double refraction, may occur in isometric crystals and in amorphous substances that have been subjected to strains.

Anisotropic Character. If a section of an anisotropic crystal were very thick and the double refraction very strong, as in calcite, a double image of a point would be seen through it with both the polarizer and analyzer out of the field. The only exception being when the line of sight was parallel to an optic axis. But as most crystals have not such strong double refraction, and as the sections studied are very thin, the following method is used to determine this *anisotropic* character or *double refraction.*

* In the Seibert microscope the analyzer or upper nicol is so fitted that it slides in and out of the tube of the microscope with its plane of vibration always at right angles to the plane of vibration of the polarizer or lower nicol.

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In Fig. 16, let P P′ be the plane of vibration of the polarizer, and A′ A the plane of vibration of the analyzer. All the light, after it has passed through the polarizer, is vibrating parallel to P P′ when it reaches the lower side of the transparent crystal, *c d e f*, on the stage of the microscope. In this transparent section let *o b* and *o a* be the two *directions* of *elasticity*, *i. e.*, the only two directions parallel to which the rays of light can vibrate in passing through the section.

Let *o m* represent the amplitude of vibration of a ray from the polarizer. When this ray reaches the section it cannot get through

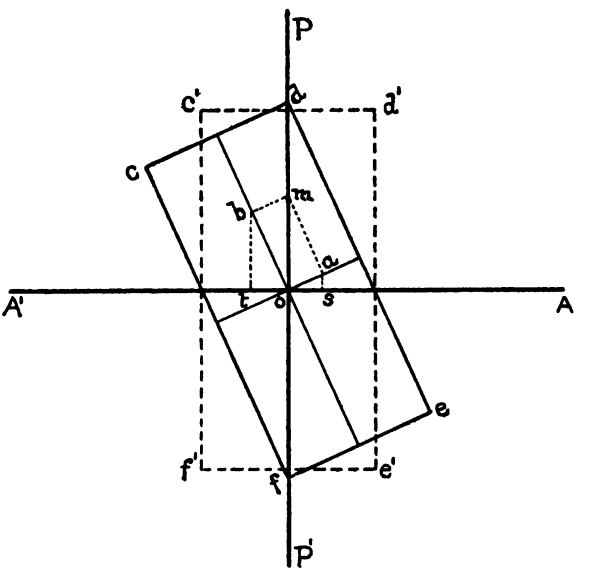

FIG. 16.

it vibrating in the direction *o m*, but a portion of it can get through vibrating in the direction *o b* and a portion vibrating in the direction *o a*. From *m* draw perpendiculars to *o b* and *o a*. Then according to the law of the parallelogram of forces *o b* will represent the amplitude of vibration of the part of the ray passing through the crystal vibrating in the direction *o b*, and *o a* will represent the amplitude of vibration of the part of the ray passing through the crystal vibrating in the direction *o a*. We have thus two rays passing through the crystal, polarized at right angles to each other.

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When these two rays come to the analyzer, whose plane of vibration is A′ A, they cannot get through vibrating in their present directions, but components of their rays, *o t* and *o s*, can get through vibrating parallel to the plane A′ A.

As the elasticities in the crystal are not equal in the directions *o b* and *o a*, the two polarized rays pass through with different velocities and on emergence one ray is slightly ahead of the other. This is still true of the components of these two rays that pass through the analyzer, vibrating parallel to its plane of vibration A′ A.

Hence we have two series of rays coming to the eye, polarized in the same plane, but one set slightly in advance of the other. These two series of rays, having their vibrations in the same plane and being in different "phase," will interfere and produce some *interference* or *polarization* color. The interference color is independent of the proper color or "absorption tint" of the crystal section.

Now suppose the stage to be rotated until the section *c d e f* takes the position *c′ d′ e′ f′*. The section will now be found to be dark and no interference color will be seen. This is due to the fact that the directions of elasticity in the section are parallel to the planes of vibration of the crossed nicols, consequently the light passes through the section still vibrating parallel to the plane P P′ of the polarizer and is all cut out by the analyzer. Darkness will occur every 90° and therefore four times during a complete rotation of the stage. The interference color is also observed to vary in intensity, but not in color, and to be at its maximum 45° from the positions of darkness.

Sections of uniaxial crystals at right angles to the optic axis (which is a direction parallel to which no double refraction takes place) act like isotropic substances and remain dark during a complete rotation of the stage. In the biaxial crystals, a section at right angles to an optic axis generally shows more or less illumination, but this illumination does not change as the stage is rotated.*

The only way to find out whether these sections are truly isotropic, or simply at right angles to an optic axis, is to test them with convergent light as described later, see p. 29.

Double Refraction, whose strength can be estimated by observing the *interference* or *polarization* colors.

* Idding's Translation, p 37, and p. 61.

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The *interference colors* of minerals with very weak double refraction vary from a bluish gray to a grayish white. As the strength of the double refraction increases the colors become the very intense bright tints of the spectrum, yellow, red, blue, green, etc., called the first and second order colors. As the strength of the double refraction still increases the colors pass through the tints of the spectrum in sequence (called orders), becoming paler until finally, when the double refraction is very strong, the colors become the neutral, almost colorless tints of the higher orders. The eye must be trained to appreciate the colors of different orders, and the student is advised to practice with mineral sections, of known strength of double refraction, and compare the resulting interference colors with a color chart.*

The interference color really depends on the thickness of the crystal section, the relative values of the axes of elasticity, *i. e.*, the strength of the double refraction, and the position of the section in the crystal. This latter condition may be the cause at times of unusual variation in the interference color. As rock sections are generally of about the same thickness † the characteristic interference colors of minerals do not usually show very much variation.

Extinction and Extinction Angles. When the section, see Fig. 16, is in such a position that its directions of elasticity are parallel to the planes of vibration of the nicols, no light can pass through the analyzer, and the section is dark. Hence the light is extinguished and this phenomenon is called *extinction.*

Extinction is said to be *parallel* or *symmetrical* when the directions or axes of elasticity are parallel to any crystallographic lines or directions, or bisect the angles between these lines. The crystallographic lines or directions may be either cleavages or the boundaries of idiomorphic crystals.

* A chart of interference colors can be obtained from Baudry et Cie, Paris, and is also published in *Les Mineraux des Roches*, by Levy and Lacroix, and in Rosenbusch's *Mikroskopische Physiographie.*

† It must be remembered that very carefully prepared sections, especially those made abroad, are usually thinner than those made more carelessly or by amateurs. Therefore the interference colors, obtained from all such minerals, will be lower in order than those which would be given by thicker sections of the minerals. A notable example would be that the feldspars, quartz and the orthorhombic pyroxenes would generally give only the grays, instead of any of the bright 1° order colors. It is well in this case to pick out some well known mineral in the section, as quartz, and note its interference color. Knowing how this varies from the normal interference color, due allowance can be made for the colors given by the other minerals.

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This kind of extinction is shown by all sections of anisotropic crystals, except those in the monoclinic and triclinic systems.

In the monoclinic system sections in the ortho zone 0 P : ∞ P$\breve{\infty}$ (001 : 100) also show it.

When the *extinction* is not symmetrical it is called *oblique*, and is shown by all sections of monoclinic crystals [except those in the ortho zone 0 P : ∞ P$\bar{\breve{\infty}}$ (001 : 100)] and triclinic crystals.

Extinction which does not take place over the whole of the section of a simple crystal at the same moment, but passes over the section like a dark wave or shadow is said to be "*wavy*;" and indicates that the crystal has been subjected to mechanical forces producing a change in the position of the axes of elasticity in different parts of the crystal, see Fig. 8.

The angle between a direction or axis of elasticity in the section, and some known crystallographic direction (as a cleavage or crystal outline) is called an *extinction angle*, and is measured in the following way: Find the positions of the directions or axes of elasticity in the section, which must be parallel to the cross-wires when extinction takes place. Note the reading on the graduated circle of the stage. Now remove the upper nicol, in order to get a more distinct view of the field, and rotate the stage until you bring some known crystallographic line into parallel position with the cross-wire selected as a reference line. Take the reading of the graduated circle again, and the difference between these two readings will be the *extinction angle*.

It can readily be seen that depending on which way the section is rotated, either a small or a large extinction angle will be obtained, the two angles being complements of each other. The extinction angle generally recorded is that between the nearest axis of elasticity and the vertical axis c.

In monoclinic minerals the maximum value of the extinction angle (the only angle of real value in differentiating the mineral) can only be obtained from a section parallel to the clinopinacoid ∞ P$\breve{\infty}$ (010); but in practice sufficiently accurate results can generally be obtained by measuring the extinction angles of all sections of the same mineral, which seem to be about parallel to the vertical axis c, and then taking the maximum value obtained. Amphibole and pyroxene can easily be distinguished in this way.

Extinction is generally tested for by revolving the stage, carrying the section, until darkness is observed; the most accurate re-

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sults being obtained by using monochromatic light. There are other more exact methods,* called Stauroscopic methods, for locating these directions or axes of elasticity. A quartz or gypsum test-plate, so prepared as to give some definite interference color as red of the 1° order, may be introduced between the two nicols, and the section revolved until this color is exactly matched. This perfect matching of color is only possible when the directions or axes of elasticity of the section are exactly parallel to the planes of vibration of the nicols, as otherwise some interference color would be produced by the section and the true color of the test-plate would not appear.

This method of testing can be employed to recognize the very weak double refraction of some minerals, whose interference colors are such dark or neutral grays as not to be noticed without this test. After the test-plate has been introduced, some slight variation in the color will be observed when the stage carrying the doubly refracting section is rotated.

Method of Testing for the Relative Value of the Two Directions or Axes of Elasticity in a Mineral Section.†

A mica, quartz or gypsum plate can be used to make this test. The directions of the maximum and minimum axes of elasticity must be known and marked on the plate.‡

The crystal section to be tested is placed on the rotating stage, between crossed nicols, and the directions or axes of elasticity determined by finding the directions of extinction. The section is now turned 45°, when the interference color will be at its maximum, and the directions or axes of elasticity will make angles of 45° with the planes of vibration of the nicols and the cross-wires in the eye-piece.

Now introduce § the test-plate, between the section and the an-

* Idding's Translation, p. 63.

† For a more elaborate discussion of this method, see Idding's Translation, p 64.

‡ In the case of the ¼ undulation mica plate these axes are easily found, as the minimum axis of elasticity *c* lies in the plane of the optic axes, *i. e.*, it is the line joining the loci of the the two black hyperbolas. The direction at right angles to this axis. *c* is an axis of greater elasticity. In the case of the gypsum and quartz plates, these axes must be carefully determined by an expert.

§ The test-plates are generally introduced in the slot *k*, in a microscope of the Seibert type, or if a cap-nicol is used in a slot below this. In case no provision is made by the instrument maker for these test-plates, the regular analyzer is left out of

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alyzer, so that its known axes of elasticity also make angles of 45° with the cross-wires in the eye-piece, bearing in mind at the same time the positions of its maximum and minimum axes of elasticity.

When the test-plate is introduced a new interference color will be noticed which is either higher or lower in the color scale * than the original interference color of the mineral section. When the known axes of elasticity of the test-plate are superposed over corresponding directions or axes of elasticity in the mineral section,

FIG. 17.—Sanidine crystal *f*, showing Carlsbad twin, and quartz *q* in rhyolite. Crossed nicols.

the effect is to thicken the section and the interference color rises in the scale.

When the axes of the test-plate are superposed over directions or axes of elasticity in the mineral section which are not corresponding, the effect is to thin the section and the interference color sinks in the scale.

Hence by observation of the interference colors it is possible to determine the relative values of the directions or axes of elasticity in the mineral section. Great care should be taken when the test-

the tube, and a simple nicol prism is used as an analyzer and is held by the observer over the eye-piece. Care must be taken to have the plane of vibration of this nicol at right angles to that of the polarizer, and to leave sufficient room for the introduction, by hand, of the test-piece between the eye-piece and the nicol. With care the plates can be introduced with sufficient accuracy to make the test practical.

* A scale or chart of interference colors should be before the observer in order to avoid any mistakes as to whether the new color is higher or lower in the scale.

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plate gives a higher interference color than the mineral section to be tested. When this is the case the effect of the mineral section on the interference color of the test-plate must be considered.

For minerals which have very strong double refraction, as zircons, so that the interference colors are of the high orders, it is advisable to use the method of testing with a quartz wedge.*

Structure.

(a) *Twinning*, generally noticed by the parts of the twin not extinguishing at the same time. It may also be observed, without crossed nicols, just as in the case of macroscopic minerals.

Twinning may be classed as: *simple*, Fig. 17; *polysynthetic*, due to repeated twinning after the same law, Fig. 12; and *crossed or "gridiron,"* due to repeated twinning after two laws, Fig. 18.

FIG. 18.—Microline, showing crossed or "gridiron" twinning. Crossed nicols.

(b) *Zonal* structure, often only made visible by the zones extinguishing at different times. It may, however, be noticed by the zones being of slightly different color, or by the zonal distribution of inclusions. In the case of the feldspars the zonal structure may be caused either by the crystal being formed of zones of different chemical composition, or by ultra-microscopic twinning,† Fig. 19.

(c) *Aggregate* structure, being a confused mass of separate little crystals, scales or grains all extinguishing at different times, Fig. 20.

(d) *Sphærulitic* structure, produced by the aggregation, in a

* See Idding's Translation, p. 65.

† Harker's *Petrology for Students*, 1895, p. 14.

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radiate form, of crystals or crystallites. It is generally easily perceived by the dark cross, resulting from the extinguishing of the

FIG. 19.—Zonal feldspar crystal (Carlsbad twin) in trachyte. Crossed nicols.

light in those crystals whose axes of elasticity are parallel to the planes of vibration of the nicols. When the stage is revolved the arms of the cross do not rotate, Fig. 20.

FIG. 20.—Sphærulites in felsite. Ground-mass shows aggregrate structure. Crossed nicols.

(e) *Pseudomorphic* structure, which may be partial or complete, and is noticed by the changed portions producing different optical effects from those of the original mineral. Sometimes, although

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the pseudomorphism has been quite complete, the form of the original mineral or crystal may still be seen, Fig. 21.

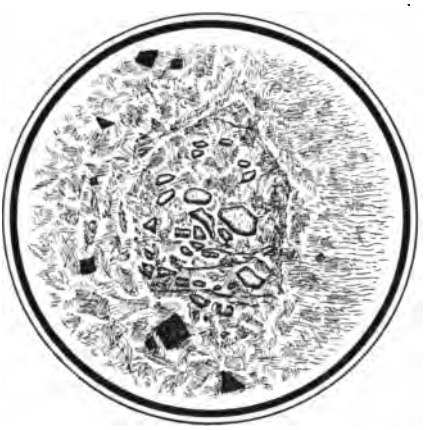

FIG. 21.—Olivine decomposed to serpentine. The pseudomorphism has been quite complete, only small portions of the original olivine remaining. The outline of the parent crystal can be quite distinctly seen. Crossed nicols.

Characters Observed by Convergent Light.

Convergent light is obtained by passing the rays of polarized light through a strong condensing lens, which generally fits like a cap over the top of the polarizer. By means of a suitable adjustment the condensing lens can be brought very close to the lower surface of the section on the stage.

The lens thus sends a cone of light through the section, and used in connection with *crossed nicols* a series of optical phenomena, called *interference figures*,* are produced. A very high power objective † must be used, and when the eye piece is removed, a small image of the interference figure will be seen.

In some microscopes an arrangement is made for getting a magnified image of the interference figure, by retaining the eyepiece and using an additional Bertrand lens.

In order to get good results care must be taken to have strong illumination and the condensing lens close up under the section. The tests are best made with monochromatic light, but with white light the effects are substantially the same, the only difference

* Idding's Translation, p. 68.

† In the Seibert microscope use No. V objective, in English microscopes a ¼″ or ⅕″ objective.

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being that the rings and curves are variously colored instead of being simply light and dark.

Isotropic substances show no *interference figures.*

Uniaxial Interference Figures.

(a) Sections normal to the optic or vertical axis *c* show a dark cross, with or without colored rings, Figs. 22 and 23.

FIG. 22.

FIG. 23.

The arms of the cross are parallel to the planes of vibration of the nicols, and the figure does not move when the stage carrying the section is rotated.

(b) Sections oblique to the optic axis show a portion of a dark cross, with or without colored rings, Fig. 24.

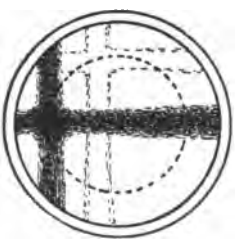

FIG. 24.

The centre of the cross is not in the axis of rotation, and as the stage bearing the section is revolved, the centre of the cross describes a circle, the arms always maintaining parallel positions.

If the section is still more oblique to the optic axis the centre of the interference cross may be outside the field of view, and only the dark arms will be seen swinging pass, when the section is rotated, thus making the figure rather indefinite.

Sections which are thick and have strong double refraction will show the cross and rings clearly and sharply defined, there being quite a number of rings crowded close together. Sections which

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are very thin and have weak double refraction show only a broad dark cross and no rings. The interference figures will vary between these extremes, depending on the thickness of the section and the strength of the double refraction.

To obtain the most characteristic figures, observations must be made on sections about normal to the optic axis, that is sections which remain dark or nearly dark during complete rotation between crossed nicols in parallel light.

Optical Character, Positive or Negative. After having obtained a uniaxial interference figure, test it by means of a ¼ undulation mica plate. This plate must be introduced between the objective * and the analyzer in such a way that its axis of elasticity ε, marked on the plate, makes an angle of 45° with the planes of vibration of the nicols.

When this is done the interference figure changes, or may more or less disappear, two dark spots or blotches being brought prominently into view. If rings are still seen it will be noticed that they have expanded in the quadrants occupied by the dark spots. This fact may make it possible to determine the optical character of a section, which is so oblique to the optic axis that the dark spots are not seen after the introduction of the mica plate.

If the optical character is *positive* the line joining these dark spots is perpendicular to the axis of the mica plate, see Fig. 25.

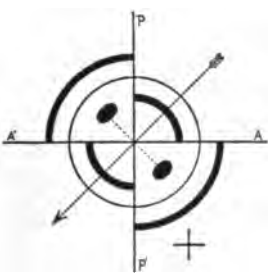

FIG. 25.

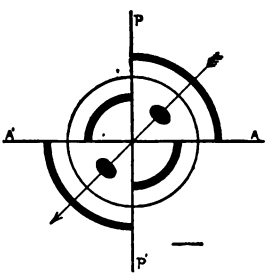

FIG. 26

If *negative* the line joining the dark spots coincides with the direction of the axis of the mica plate, see Fig. 26.

The (+) and (—) character is easily determined by remembering that the line, joining the dark spots, makes the + and — sign

* In the Seibert microscope there is a little slot *k* for this purpose just above the objective.

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respectively with the axis of the mica plate. The axis of the mica plate (represented in the figures by an arrow) is of course not seen, but its position must be borne in mind when making this test.

If the mica plate does not give satisfactory results, which will be the case when the broad cross of a weak doubly refracting crystal is to be tested, use a quartz or selenite plate, cut the proper thickness to give the red color of the first order.

This plate must be introduced with its relatively greater axis of elasticity (previously determined and selected as a matter of convenience) making an angle of 45° with the planes of vibration of the nicols. Instead of the dark spots being seen there will appear two blue and two red quadrants. The diagonally opposite quadrants being of the same color.

In determining the (+) and (—) character consider the blue quadrants as the equivalent of the dark spots in the preceding case.*

Biaxial Interference Figures.

(a) Sections normal to an optic axis exhibit the interference figure shown in Fig. 27. As the stage, carrying the section, is ro-

FIG. 27.

tated the bar changes into a hyperbola and back again into a bar.

As previously stated sections of biaxial crystals, normal to an optic axis, do not remain perfectly dark during rotation of the stage between crossed nicols in parallel light. On the contrary these sections of biaxial crystals remain uniformly illuminated.†

(b) Sections normal to the acute bisectrix (see p. 6), exhibit interference figures like those shown in Figs. 28 and 29.

FIG. 28.

FIG. 29.

* The optical character may be determined in parallel light by proving $c' = c$ (+), $c = a$ (—).

† Idding's Translation, pp. 37 and 119.

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Fig. 28 shows the appearance of the interference figure when the plane of the optic axes is parallel to the plane of vibration of either nicol, and Fig. 29 shows the appearance when this plane is inclined 45° to the planes of vibration of the nicols.

As the stage, carrying the section, is rotated the dark cross changes into two hyperbolas, which again unite to form a cross.

The centers of the small ellipses and the black hyperbolas mark the loci of the optic axes, and therefore indicate approximately the size of the *axial angle*, 2 *E*.

Sections in other positions, relative to the optic axes, give interference figures less definite in appearance than those just described; and the same conditions affect the appearance of these figures as in the case of uniaxial crystals. Very thin sections, of weak double refraction, may only show indistinct dark crosses or hyperbolas without any ellipses.

The section normal to the acute bisectrix, which gives the most characteristic interference figure, cannot generally be recognized except by an examination in convergent light. Therefore no clue can be obtained as to the best section to test, and the safest method is to test all the sections of the mineral occurring in the rock section.

It must be remembered that this uncertainty, in the choice of sections for testing, does not exist in uniaxial crystals; where the best sections are indicated by the fact that they remain dark or nearly so during complete rotation between crossed nicols.

The uniaxial or biaxial character of a mineral section, which only shows an indistinct bar, may be determined as follows: A bar (one arm of the cross) of a uniaxial interference figure moves in the same direction as the rotating stage, and always remains straight, while the biaxial bar moves in the opposite direction to that of the stage and becomes curved.

Optical Character, Positive or Negative. When the axial angle is very small, so that the interference figure approaches that of a uniaxial crystal, the methods used for testing uniaxial figures are employed.

When, however, the axial angle is large, the following method can be used:

After having obtained an interference figure, from a section as nearly at right angles to the acute bisectrix as possible, the stage is rotated until the plane of the optic axes (the trace of which on

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the plane of the section is the line joining the loci of the two optic axes) makes an angle of 45° with the planes of vibration of the crossed nicols or the cross-wires in the eye-piece.

A quartz wedge* is now pushed in between the mineral section and the analyzer,† so that its axis $c = \mathfrak{c}$ (previously determined and marked on the wedge) is either at right angles or parallel to the plane of the optic axes of the mineral section.

The optical character of the mineral is *positive* when the ellipses, surrounding the loci of the two optic axes, appear to expand or open out when the quartz wedge is pushed in with its axis parallel to the plane of the optic axes.

The optical character is *negative* when the ellipses appear to expand or open out when the wedge is pushed in with its axis at right angles to the plane of the optic axes.

As the ellipses expand they move from the loci of the optic axes towards the centre of the interference figure, and finally open into lemniscates which move outward from the plane of the optic axes.

Even when the section is very thin and the double refraction very weak, only the black hyperbolas without ellipses being seen, the test can be made; and colored ellipses will appear, after the pushing in of the quartz wedge, which will act in the same way as the normal ellipses of the interference figure.

Resumé of the Uses of Parallel and Convergent Light.

Parallel light is used to distinguish between isotropic and anisotropic substances, to locate directions and axes of elasticity, and to measure extinction angles and the relative values of the axes of elasticity.

Convergent light is used to distinguish between uniaxial and biaxial crystals, to determine whether a section that appears to be isotropic is really so or only normal to an optic axis and to determine the optical character and dispersion.

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* For construction of quartz wedge and a more detailed description of the method of determining optical character, see *Iddings' Rosenbusch*, p. 65.

† The wedge can be introduced in either of the several ways described for the introduction of the test-plates on p. 25.

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CHAPTER IV.

The Microscopic and Optical Characters of Minerals.

OPAL.

Isotropic. Amorphous.

Composition: SiO_2. $n\ H_2O$, generally soluble in caustic alkalies.

Usual Appearance in Sections: Colorless patches or veins, also at times with sphærulitic structure and feeble negative double refraction. The *relief* is so low ($n = 1.45$) that the opal portion may be mistaken for a hole in the section filled with balsam.

Remarks: Found as a secondary mineral in many acid volcanic rocks, rhyolite, trachyte, andesite, etc., and also in basic basalts. H., 5.5 to 6.5. Sp. gr., 2.2.

LIMONITE.

Amorphous.

Composition: $Fe_2(OH)_6$, Fe_2O_3, frequently quite impure.

Usual Appearance in Sections: Brownish and opaque, in very thin sections may be translucent.

Remarks: Limonite is essentially a decomposition product, often forming pseudomorphs after ferruginous silicates or halos about the iron ores.

PYRITE, Pyrites.

Isometric.

Composition: FeS_2.

Usual Appearance in Sections: Cubes, pentagonal dodecahedrons, or combinations of these forms. Sometimes in irregular grains. Outline of cross-sections generally square.

Opaque, and by incident light, bright yellow, with strong metallic lustre.

Alters very easily to the oxides of iron (rust).

Remarks: May be present in all kinds of rocks, and abundant in igneous and sedimentary rocks. Not noticeably acted on by hydrochloric acid. H., 6 to 6.5. Sp. gr., 4.9 to 5.2.

PYRRHOTITE, Magnetic Pyrites.

Composition: Fe_6S_7 to $Fe_{11}S_{12}$. Distinguished from pyrite by being practically always in irregular masses and not in crystals, and by bronze yellow color in incident light. Found in gabbro, more rarely in schists.

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MAGNETITE, Magnetic Iron Ore.

ISOMETRIC.

COMPOSITION: Fe_3O_4, often contains Ti.

Usual Appearance in Sections: Grains and crystals (generally octahedra), Fig. 30 B. Skeleton crystals frequent in highly ferruginous eruptive rocks.

Twinning.—Common, according to *Spinel* law.

Opaque, and by incident light, bluish-black, with strong metallic lustre.

Differentiation: From HEMATITE, CHROMITE, ILMENITE and GRAPHITE, by being easily separated from powdered rock by weak magnet.

FIG. 30.—*A* Zircon crystals (isolated from granite) in balsam, showing high relief. *B* Magnetite crystals. *C* Ilmenite, showing partial decomposition to *leucoxene* along crystallographic directions.

REMARKS: Very widely distributed in eruptive rocks and crystalline schists. In the eruptive rocks magnetite belongs to the oldest secretions from the magma, immediately followed by chrysolite, biotite, hornblende, augite, etc.; hence often appears as inclusions in these and other minerals. Magnetite grains may form with other substances, pseudomorphs after hornblende, biotite, hypersthene, etc. Such pseudomorphs appear to be caused by "resorption." Magnetite is strongly magnetic and soluble in hydrochloric acid. H., 5.5 to 6.5. Sp. gr., 4.9 to 5.2.

CHROMITE.

ISOMETRIC.

COMPOSITION: $FeCr_2O_4$.

Usual Appearance in Sections: Octahedral crystals and grains like magnetite. May be surrounded by green halo of chrome ochre.

Differentiation:

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(*a*) From MAGNETITE by having weak metallic lustre and grayish-black to black color (by incident light); or by being transparent in very thin sections, when it has no metallic lustre and is brown to reddish-brown in color (by transmitted light), with a very rough surface due to high index of refraction.

(*b*) From SPINEL (Picotite), see under Spinel.

REMARKS: Common in crystalline rocks, rich in magnesia, and in serpentine. Chromite is not acted on by acids, is non-magnetic and gives chromium bead test. H., 5.5. Sp. gr., 4.3 to 5.6.

SPINEL.

ISOTROPIC. ISOMETRIC.

COMPOSITION: $Mg(AlO_2)_2$. Pleonaste (Fe, Mg spinel), Picotite (Cr spinel).

Usual Appearance in Sections: Grains and octahedral crystals, never decomposed in rocks. Colorless or light red to dark green (pleonaste)* to brown (picotite). *Relief* high and surface rough ($n = 1.715$ for spinel proper.)

Differentiation: From GARNETS by the more common green color, undecomposed condition and slightly lower relief. Picotite can only be distinguished from chromite chemically or by density and hardness.

REMARKS: Found in gneiss, granulite, (pleonaste) eruptive rocks and regions of contact metamorphism, (picotite) olivine-basalt and serpentine. Spinels are insoluble in hydrochloric acid. H., 8. Sp. gr, 3.5 to 4.1.

GARNET.

ISOTROPIC. ISOMETIC.

COMPOSITION: $R''_3 R'''_2 (SiO_4)_3$. R″ is Ca, Mg, Fe or Mn; R‴ is Al, Fe‴, or Cr, rarely Ti.

Usual Appearance in Sections: Irregular grains, Fig. 13, somewhat resembling spots of gum; also simple crystals, showing forms ∞O (110) and $2O2$ (211), alone or in combination, Fig. 14 *b*. Zonal structure not infrequent.

Color.—Colorless, or nearly so, to yellowish to reddish.

Index of Refraction.—$n = 1.746 - 1.814$.

Relief.—High and surface rough.

Fracture.—Irregular cracks occur, but no cleavage noticed.

Crossed Nicols: As garnets are isotropic, sections remain dark during complete rotation. Optical anomalies may however occur, but the double refraction is very weak.

Alteration: Garnets are usually fresh, but may be found altered to chloritic matter.

Differentiation: From SPINEL.—See under the latter.

REMARKS: Found principally in granulites, metamorphic rocks, mica-schists, etc. Garnets are practically insoluble in hydrochloric acid. H., 6.5 to 7.5. Sp. gr., 3.4 to 4.3. The insolubility in acids and the high sp. gr. help in separating garnet from a powdered rock.

* May be almost opaque and black by incident light, without metallic lustre.

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LEUCITE.

ISOTROPIC. ISOMETRIC.*

COMPOSITION: $KAl(SiO_3)_2$.

Usual Appearance in Sections: Crystals or grains, which vary greatly in size. Cross-sections often nearly round.

Color.—Colorless.

Index of Refraction.—$n = 1.508$.

Relief.—None and surface smooth.

Fracture.—May be noticed, but no cleavage observed.

Inclusions.—Symmetrically or zonally arranged, consisting of the older secretions associated with leucite, as magnetite, apatite, chrysolite, augite, etc. Smaller crystals free from inclusions.

Crossed Nicols: The smaller crystals appear isotropic; the larger crystals show characteristic intersecting systems of twin-lamellæ, Fig. 31.

FIG. 31.—Leucite, showing complicated, interpenetration twinning between crossed nicols.

Double Refraction.—Very weak ($\gamma - \alpha = 0.001$). In thin sections it may be necessary to use a sensitive color-plate to prove double refraction.

Interference Colors.—Very low 1st order, dark bluish-gray, etc.

* The system of crystallization of leucite has been the subject of much discussion. Its habit is isometric. The consensus of opinion seems to be that leucite crystallizes in the isometric system, but that the isometric molecular arrangement, at least of the larger crystals, cannot exist for the temperature and pressure at the earth's surface. Hence molecular displacement takes place, giving rise to a more or less complicated apparent twinning, and optical anomalies are noticed. The isotropic character returns if the section is heated to 500°C. *Iddings' Rosenbusch*, p. 133.

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Alteration: Quite frequent to fibrous or granular zeolites.

REMARKS: Almost entirely confined to younger eruptive rocks, phonolite, tephrite and other leucite rocks and their tuffs. Often found with plagioclase, nephelite, augite, etc. It is more or less attached by hot hydrochloric acid. H., 5.5 to 6. Sp. gr., 2.4 to 2.5. The isolation of leucite from rock powder can be better accomplished by specific gravity than by chemical methods.

SODALITE GROUP.

Sodalite, Haüynite and Noselite.

ISOTROPIC. ISOMETRIC.

Sodalite.

COMPOSITION: $3\,NaAlSiO_4 + NaCl$.

Usual Appearance in Sections: Allotriomorphic or idiomorphic, rarely twinned. Colorless or bluish, yellowish, etc. No *relief* and surface smooth ($n = 1.49$). Cleavage imperfect. Inclusions, when abundant, accumulated centrally. Optical anomalies may occur.

Alteration: Produces tufted aggregates of zeolites, etc.

Differentiation: From NEPHELITE (Elæolite) by being isotropic.

REMARKS: Common in elæolite-syenite and found in trachyte and phonolite. Its formation followed that of the iron-bearing constituents and preceded that of the feldspars. Gelatinization test can be made with hydrochloric acid, and many common salt crystals will be noticed when jelly dries. H., 5 5 to 6. Sp. gr., 2.3.

Haüynite (Haüyne).

COMPOSITION: $2\,(Na_2,Ca)\,Al_2(SiO_4)_2 + (Na_2,Ca)SO_4$.

Blue or colorless, idiomorphic crystals or grains, often with dark decomposition border. Inclusions are abundant, marginally or zonally arranged, or in lines parallel to the octahedral axes. When gelatinization test is made many gypsum crystals ($CaSO_4 + H_2O$) are noticed.

Like sodalite in its other properties.

Noselite (Nosean).

COMPOSITION: $2Na_2Al_2Si_2O_8 + Na_2SO_4$.

Colorless or yellowish. Like haüynite and distinguished by micro-chemical tests. When gelatinization test is made few, if any, gypsum crystals are noticed (absence of Ca).

When heated noselite remains unchanged, while haüynite turns blue; but this test will not work if the minerals are decomposed.

REMARKS: Haüynite and noselite are found in rocks poor in silica and rich in alkali. They are very common in phonolite and leucite-porphyry.

PEROVSKITE, Perofskite.

ISOTROPIC. ISOMETRIC.

COMPOSITION: $CaTiO_3$.

Usual Appearance in Sections: Microscopic grains or crystals, pale brownish in color and not very transparent. *Relief* very high ($n = 2.35$), like titanite.

Between *crossed nicols*, crystals often appear weakly doubly refracting, probably on account of optical anomalies. The larger crystals may show a complicated penetration twinning.

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Differentiation: When opaque it might be mistaken for the iron ores, but has no metallic lustre.

REMARKS: Found in the younger basic eruptive rocks, especially melilite-basalt. Commonly associated with the iron ores, nephelite, augite and chrysolite. Insoluble in hydrochloric acid. H., 5.5. Sp. gr., 4.1.

RUTILE.

ANISOTROPIC. UNIAXIAL. TETRAGONAL.

COMPOSITION: TiO_2 $c = \mathfrak{c}$. ELONGATION $\parallel \mathfrak{c}'$.

Usual Appearance in Sections: Sharp, elongated, prismatic crystals when microscopic, but granular when the individuals are large. Grains may be almost opaque, with metallic lustre by incident light. Geniculated twins very common. Small crystals sometimes form net-shaped groups (sagenite), by crossing one another at angles of 60°. Color yellowish to reddish-brown. *Relief* very high and surface rough ($n' = 2.712$). Prismatic cleavage not observed in microscopic crystals. Pleochroism not marked.

Crossed Nicols: Double refraction *very* strong ($\gamma - a = 0.287$). Interference colors * very high order, hence may not be noticed when rutile is strongly colored. Interference colors of very minute needles brilliant. *Extinction* parallel to prisms. In *convergent light* optical character (+).

Alteration: May take place to a white or yellowish, fibrous or granular substance, strongly refracting, and similar to the alteration product of ilmenite.

REMARKS: Found in the metamorphic schists, amphibolites, slates, etc.; also as inclusions in quartz and mica. The "sagenite" webs of the decomposed micas are probably secondary. Rutile is insoluble in hydrochloric acid. H., 6 to 6.5. Sp. gr., 4.2. It is easily separated from rock powder by its insolubility in acid and its high sp. gr. It can be distinguished from zircon and cassiterite in concentrates by chemical tests.

ZIRCON.

ANISOTROPIC. UNIAXIAL. TETRAGONAL

COMPOSITION: $ZrSiO_4$. $c = \mathfrak{c}$. ELONGATION $\parallel \mathfrak{c}'$.

Usual Appearance in Sections: Small, short prismatic crystals, Fig. 30 A, and grains. When enclosed in black-mica, hornblende, cordierite, etc., often surrounded by characteristic pleochroic halo.

Color.—Colorless, rarely pale brownish. Coloration may be zonal.

Index of Refraction.—$n' = 1.94$.

Relief.—Very high, and surface rough.

Polarized Light:

Pleochroism.—Not usually noticeable, but when observed very little absorption takes place $\parallel c$.

* The interference colors of all minerals here recorded are those given by sections 0.03 *mm.* in thickness (very thin sections).

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Crossed Nicols:

Double Refraction.—Very strong ($\gamma - a = 0.055$ to 0.062).

Interference Colors.—Very high (4th) order, minute crystals show brilliant colors.

Extinction.—As zircon is uniaxial, basal sections remain dark during rotation of stage. In all other sections extinction is parallel to c.

Convergent Light: Basal sections, which are large enough to give interference figures, show several rings in addition to dark cross. Optical character (+).

Alteration: Very rarely takes place.

Differentiation: From APATITE.—By much higher relief and stronger double refraction.

REMARKS: Found abundantly in eruptive and metamorphic rocks; common in granite, syenite, diorite, gabbro, gneiss, etc. It is one of the oldest constituents of the rocks in which it occurs, and may often be found as inclusions in the ferro-magnesium minerals. Zircon is insoluble in hydrochloric acid. H., 7.5. Sp. gr., 4.5 to 4.7. It can easily be separated from rock powder on account of its high sp. gr., insolubility in acid and non-magnetic properties. The crystals can then be examined separately, or chemical tests made to prove the presence of Zr and the absence of Ti (distinction. from rutile and titanite).

SCAPOLITE GROUP, Wernerite.

ANISOTROPIC. UNIAXIAL. TETRAGONAL.

COMPOSITION: Silicates of Ca, Al and Na. $c = a$. ELONGATION $\| a'$.

Usual Appearance in Sections: Colorless, allotriomorphic grains or (dipyre) prisms. *Relief* not marked ($n' = 1.553$ to 1.585), about the same as quartz. Cleavage distinct, parallel to square prism.

Crossed Nicols: Double refraction strong ($\gamma - a = 0.012$ to 0.036), weaker in dipyre. Interference colors 2d order, more brilliant than those of most of the colorless minerals. Basal sections (showing cleavages intersecting at 90°) isotropic. *Extinction* parallel in longitudinal sections. In *convergent light* basal sections show distinct uniaxial interference figures; optical character (—).

Alteration: Takes place easily to a fibrous substance or to kaolin, muscovite, etc.

Differentiation:

(*a*) From FELDSPARS (not showing twinning) and IOLITE (Cordierite) by uniaxial character, cleavage and higher order interference colors.

(*b*) From QUARTZ by cleavage, higher order interference colors and optical character; quartz is (+).

(*c*) From APATITE (in grains) by lower index of refraction, cleavage and higher order interference colors.

REMARKS: Found in gneisses, crystalline schists and metamorphosed limestones. Dipyre occurs in contact zones of limestones and schists, where it might be confused with andalusite, but cross-sections show uniaxial character. The minerals of this group are more or less soluble in hydrochloric acid. H., 5.5. Sp. gr., 2.68.

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VESUVIANITE, Idocrase.

ANISOTROPIC. UNIAXIAL. TETRAGONAL.

COMPOSITION: $Ca_{24}Al_{12}(OH)_{10}Si_{20}O_{77}$. ? $c = a$. ELONGATION $\parallel a'$.

Usual Appearance in Sections: Allotriomorphic grains or prismatic aggregates. Almost colorless to brownish, sometimes with zonal coloring. *Relief* high and surface rough ($n' = 1.721$). Cleavage imperfect, parallel to prism. Pleochroism generally very faint.

Crossed Nicols: Double refraction very weak ($\gamma - a = 0.002$), may vary in different portions of the same crystal (optical anomalies). Interference colors very low 1st order, dark gray, etc. Basal sections isotropic. *Extinction* parallel in sections elongated $\parallel c$ axis. In *convergent light* basal sections show a faint cross; optical character generally (—).

Alteration: Not known in rock-making vesuvianite.

Differentiation: From EPIDOTE (Pistacite) by the very low order interference colors.

REMARKS: Found in limestones, that have undergone alteration by contact with igneous rocks, and in metamorphic schists. It is insoluble in hydrochloric acid. H., 6.5. Sp. gr., 3.3 to 3.8.

MELILITE.

ANISOTROPIC. UNIAXIAL. TETRAGONAL.

COMPOSITION: $Ca_{12}Al_4Si_9O_{36}$, with at times also Na, Mg and Fe.

$c = a$ ELONGATION $\parallel c'$.

Usual Appearance in Sections: Almost colorless, tabular ($\parallel$ base) crystals or allotriomorphic. Sections very commonly lath-shaped, and often characterized by the peculiar "peg-structure,"* the lines or markings being $\parallel c$ ($\perp$ elongation of the section). *Relief* rather marked ($n' = 1.631$), higher than that of the other associated colorless minerals. Cleavage, parallel to base, very imperfect.

Crossed Nicols: Double refraction very weak ($\gamma - a = 0.005$), may only be noticed by testing with a sensitive color-plate. Interference colors the lower 1st order, grays, etc. *Extinction* parallel to cleavage or the peculiar markings or lines. Optical character (—).

Alteration: Takes place frequently to a fibrous aggregate.

Differentiation: From NEPHELITE by higher relief, shape and "peg-structure."

REMARKS: Abundant in the leucite and nephelite rocks (associated with these minerals and with augite, perovskite and chrysolite), and takes the place of a feldspar in the melilite-basalt. It gelatinizes easily with hydrochloric acid. H., 5. Sp. gr., 2.9.

GRAPHITE.

HEXAGONAL.

COMPOSITION: C.

Usual Appearance in Sections: Minute particles, or flakes and grains of irregular shape, seldom crystallized.

Opaque, and by incident light, black with metallic lustre.

REMARKS: Graphite is widely distributed in the oldest rock formations, especially in the mica slates. It also occurs in the archæan and metamorphic rocks, and is often associated with the iron oxides. Graphite is not acted on by acids. H., 1 to 2. Sp.

* *Iddings' Rosenbusch*, p. 160.

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gr., 2.09 to 2.25. It is burnt with great difficulty in thin sections on platinum foil; but this test may vary, in many cases the graphite not being consumed even after long heating.

Carbonaceous Matter.—Occurs in opaque, grayish-black particles or flakes, having no lustre; and is found finely disseminated, sometimes in larger aggregations, in sedimentary rocks.

HEMATITE.

HEXAGONAL.

COMPOSITION: Fe_2O_3.

Usual Appearance in Sections: Irregular scales, minute grains or earthy. Distinct crystalline forms not often observed in rocks.

Opaque, and by incident light, black with tinge of red and metallic lustre, or red without lustre. May also be transparent in red tints. No pleochroism observed.

REMARKS: Found widely distributed in acid eruptive rocks, crystalline schists, etc. Also as inclusions in minerals giving them their red color. It is insoluble in hydrochloric acid, and non-magnetic, unless attached to grains of magnetite. H., 5.5 to 6.5. Sp. gr., 4.9 to 5.3.

ILMENITE, Menaccanite.

HEXAGONAL.

COMPOSITION: $(FeTi)_2O_3$.

Usual Appearance in Sections: Irregular masses, without crystallographic outline, or rhombohedral crystals.

Opaque, and by incident light, iron-black with brownish tinge and metallic lustre.

Alteration: Often takes place to a whitish, strongly refracting, substance only slightly transparent, called *leucoxene*. This alteration product frequently develops along definite rhombohedral directions, Fig. 30 c.

Differentiation: From MAGNETITE.—By occurring in irregular masses, and by whitish, strongly refracting decomposition product. At times the distinction may be very difficult.

REMARKS: Ilmenite belongs to the oldest secretions from the magma, and its distribution in rocks is very great. It is found in basic igneous rocks, especially gabbro, diabase, etc. Ilmenite is attacked slowly by hot hydrochloric acid, and the solution when heated with tin becomes violet. Pure ilmenite is indifferent towards the magnet, hence strong magnetic properties would indicate a mixture with magnetite. H., 5 to 6. Sp. gr., 4.5 to 5.

CORUNDUM.

ANISOTROPIC. UNIAXIAL. HEXAGONAL.

COMPOSITION: Al_2O_3. $c = a$.

Usual Appearance in Sections: Prisms, grains or plates. Colorless or with patches or zones of blue. *Relief* very high and surface rough ($n' = 1.764$). Rhombo-

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hedral cleavage may show in larger individuals. Pleochroism only marked when color is deep.

Crossed Nicols: Double refraction weak ($\gamma - \alpha = 0.009$), like quartz. Interference colors middle 1st order, white to yellow. *Extinction* parallel in elongated sections. Optical anomalies may be noticed. In *convergent light* basal sections show a rather indistinct cross; optical character (—).

REMARKS: Found in metamorphic schists, granite, etc. It is insoluble in hydrochloric acid. H., 9. Sp. gr., 3.9 to 4.

QUARTZ.

ANISOTROPIC. UNIAXIAL. HEXAGONAL.

COMPOSITION: SiO_2.

Usual Appearance in Sections: Allotriomorphic in the granitoid rocks, when apparently the last mineral to form, Fig. 6. Chemically corroded crystals in the porphyritic rocks. Rounded grains in the "clastic" rocks. Very rarely in distinct crystals in any rocks. May at times be mutually interpenetrated with an acid feldspar (the areas of quartz and feldspar extinguishing at the same time), producing "micropegmatitic" structure.

Color.—Colorless, although by incident light it may appear colored or cloudy if it contains many inclusions.

Index of Refraction.—$n' = 1.547$.

Relief.—None and surface smooth.

Cleavage.—Rarely noticed, an important fact in determining quartz.

Inclusions.—Minute fluid and gas inclusions, often in irregular trains, are very characteristic of quartz in granitic rocks and crystalline schists. The inclusions are not so abundant in quartz in porphyritic rocks. Rutile, amphibole, etc., may occur as needle-like inclusions in quartz.

Polarized Light:

Pleochroism.—None.

Crossed Nicols:

Double Refraction.—Weak ($\gamma - \alpha = 0.009$).

Interference Colors.—The middle 1st order, white, yellow, etc.

Extinction.—As quartz is uniaxial, basal sections remain dark during a complete rotation of stage. In all other sections extinction takes place, but, due to the absence of cleavage and crystallographic outlines, is not characteristic. Thin sections do not show circular polarization.

Convergent Light: Basal sections show a dark cross, without any rings. Optical character (+).

C = C

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Alteration: Does not take place, so quartz always appears fresh and unweathered in sections.

Differentiation:

(*a*) From SANIDINE (in grains).—By use of convergent light. Feldspar is biaxial, or sections which appear uniaxial are (—).

(*b*) From NEPHELITE.—By absence of hexagonal outline, stronger double refraction and fresh, unweathered appearance.

(*c*) From IOLITE (Cordierite), SCAPOLITE and TOPAZ.—See under the latter minerals.

REMARKS: Quartz occurs widely distributed, as in the great sandstone formations. It is also a characteristic mineral of all acidic rocks, being common in granite, rhyolite, quartz-diorite, dacite, etc. Quartz may show traces of mechanical deformation by peripheral shattering of the larger grains or by "wavy extinction;"* and also evidences of chemical corrosion by curved and looped contours. The "secondary enlargement" of quartz in clastic rocks may be noticed by the deposition of silica in crystallographic orientation around the clastic grains,† the new portion extinguishing at the same time as the core. Quartz is not attacked by ordinary acids. H., 7. Sp. gr., 2.6 to 2.7.

Chalcedony.—This concretionary variety of quartz has a radially fibrous structure and shelly parting. It may form sphærulites, central sections through which show a dark cross between crossed nicols, or line cavities in rocks.

The index of refraction is a little lower than for ordinary quartz and the double refraction a little stronger. The optical character is (—), which must be determined by a mica or gypsum plate. $\dot{c} = \mathfrak{a}$. Elongation $\parallel \mathfrak{a}'$.

Chalcedony occurs in the ground mass of very silicious porphyritic rocks, which have microfelsitic development; and is found as a secondary mineral in all kinds of silicate rocks.

TRIDYMITE.

Usual Appearance in Sections: This form of SiO_2, which is soluble in boiling caustic soda, appears in "tile-like" aggregates of minute colorless plates (pseudo-hexagonal). The *relief* is extremely low.

Between *crossed nicols* the interference colors are very low in order, and the tablets may show a division into different areas.

REMARKS: Chiefly a volcanic mineral, found in rhyolite, trachyte and andesite. Commonly associated with opal and chalcedony.

CALCITE.

ANISOTROPIC. UNIAXIAL. HEXAGONAL.

COMPOSITION: $CaCO_3$. Ca may be replaced by small quantities of Mg, Fe, Mn, etc. $\dot{c} = \mathfrak{a}$.

* See page 24.

† R. D. Irving, *Am. Jour. Sci.*, June, 1883.

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Usual Appearance in Sections: Grains and aggregates. May be fibrous or oölitic. Never in crystals in rocks.

Twinning.—Polysynthetic parallel to $-\frac{1}{2}$ R ($0\bar{1}12$). Very common in crystalline limestones, and may have been produced by pressure. Shows itself between crossed nicols as a series of light and dark bands, Fig. 32.

Color.—Colorless when pure, but may appear colored by transmitted light, due to organic pigments.

Index of Refraction.—$n' = 1.601$.

Relief.—Not marked and surface rather smooth.

Cleavage.—Parallel to rhombohedron R ($10\bar{1}1$), appearing in thin sections as many sharp cracks, whose angles of intersection depend on the position of the section. Newton's colors may be seen along cleavage cracks.

Inclusions.—Fluid inclusions frequent.

Polarized Light:

Pleochroism.—No change of color observed, but absorption of ordinary ray can be noticed when section is not too thin.

FIG. 32.—Calcite grain, showing polysynthetic twinning between crossed nicols. *A.* Serpentine. *Ophiolite*, Essex Co., N. Y.

Crossed Nicols:

Double Refraction.—Very strong ($\gamma - \alpha = 0.172$).

Interference Colors.—Pale, iridescent colors of very high order.

Extinction.—As calcite is uniaxial, basal sections remain dark during rotation. Extinction is symmetrical to the interesting cleavage cracks when they appear.

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Convergent Light: Basal sections, even when very thin, show distinct interference figures, with cross and rings. Optical character (+).(−)

Differentiation:

(*a*) From other CARBONATES.—By ease with which it is attacked by cold dilute acids, test can be made on slide after removing cover.

(*b*) From MAGNESIUM-BEARING CALCITE.—By micro-chemical tests.

REMARKS: Calcite is very widely distributed, in addition to the extensive sedimentary limestone deposits. It is often a secondary product in the more basic igneous rocks, generally in such cases not showing good cleavage (Weinschenk). Mechanical deformation may be recognized by curving of the cleavage cracks and "wavy" extinction. Calcite is easily attacked and completely dissolved with effervescence by cold dilute acids. H., 3. Sp. gr., 2.72.

DOLOMITE.

ANISOTROPIC. UNIAXIAL. HEXAGONAL.

COMPOSITION: $(Ca.Mg)Co_3$, when pure $CaO = 30.4$, $MgO = 21.7$, $CO_2 = 47.8$. Proportions of Mg and Ca vary, and Fe and Mn also occur. $\dot{c} = \alpha$.

Usual Appearance in Sections: In rocks chiefly as crystals, even dense homogeneous aggregates showing tendency towards crystalline boundaries (saccharoidal structure). Crystals almost always unit rhombohedron R $(10\bar{1}1)$, with tendency to curved surfaces.

The microscopic characters are similar to those of calcite, from which it may be *differentiated* by slightly higher relief * ($n' = 1.622$), not being so easily attacked by cold dilute acid (test can be made on slide with cover off), and by tendency towards crystalline boundaries.

REMARKS: Occurs in sedimentary formations and as crystals in limestone and other rocks. Only slightly attached by cold dilute acids, but if acid is heated it dissolves easily with effervescence.

APATITE.

ANISOTROPIC. UNIAXIAL. HEXAGONAL.

COMPOSITION: $Ca_5(Cl.F)(PO_4)_3$. $\dot{c} = \alpha$. ELONGATION $\| \alpha'$

Usual Appearance in Sections: Minute, slender, hexagonal

* Some confusion may arise in regard to this distinction between calcite and dolomite. The difference in *relief* is very slight, but just enough to place dolomite on the other side of the arbitrary line in the scheme between "no marked relief" and "medium relief."

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prisms, cross-sections having regular hexagonal boundaries; and grains. Crystals often in clusters, Fig. 14 *a*.

Color.—Generally clear, bright white.

Index of Refraction.—$n' = 1.637$.

Relief.—More marked than that of the colorless associated minerals.

Cleavage.—Seldom observed microscopically.

Parting.—Long columnar crystals generally show a transverse jointing, so that the pieces may be more or less separated.

Polarized Light:

Pleochroism.—None shown by the white crystals.

Crossed Nicols:

Double Refraction.—Weak ($\gamma - \alpha = 0.004$).

Interference Colors.—The lower 1st order, generally grayish-blue or white.

Extinction.—As apatite is uniaxial, basal sections remain dark during rotation of stage. In all other sections extinction is parallel to c axis.

Convergent Light: Basal sections show a cross, without rings. Optical character (—).

Alteration: Does not take place, apatite being found perfectly fresh in decomposed rocks, which is quite remarkable considering its easy solubility in acids.

Differentiation:

(*a*) From NEPHELITE.—Relatively much smaller and longer than the nephelite crystals, which are often decomposed. Also by higher relief and negative results with gelatinization test.

(*b*) From ZIRCON and SILLIMANITE, see under the latter minerals.

(*c*) From FELDSPARS (when granular).—By higher relief and uniaxial interference figure.

REMARKS: Found in most igneous rocks and crystalline schists. In the eruptive rocks it appears as one of the oldest secretions from the magma, and hence is often found as inclusions in other minerals, especially biotite, hornblende, etc. The little crystals may be surrounded by pleochroic halos. Apatite is easily soluble in hydrochloric and nitric acids. H., 4.5 to 5. Sp. gr., 3.19. On account of its high sp. gr., apatite, in rock powder, comes down in heavy solutions with the metallic minerals, and can be separated from them by the use of a magnet. This residue can also be tested for phosphorus in the wet way with ammonium molybdate.

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NEPHELITE,* Nepheline, Elæolite.

ANISOTROPIC. UNIAXIAL. HEXAGONAL.

COMPOSITION: $7NaAlSiO_4 + NaAl(SiO_3)_2$, with partial replacement of Na by K or Ca. $\dot{c} = a$.

Usual Appearance in Sections: Nephelite in short hexagonal prisms and grains in the younger volcanic rocks, elæolite allotriomorphic in the older plutonic rocks.

Color.—Colorless.

Index of Refraction.—$n' = 1.543$.

Relief.—None.

Cleavage.—Imperfect, parallel to prism ∞P ($10\bar{1}0$) and base 0 P (0001). More marked in elæolite than in nephelite, especially when decomposition has commenced.

Inclusions.—Microscopic needles of augite, etc., also fluid and gas. Mostly in zones.

Polarized Light:

Pleochroism.—None.

Crossed Nicols:

Double Refraction.—Very weak ($\gamma - \alpha = 0.005$), may only be detected by using a test-plate.

Interference Colors.—The lower 1st order, grayish-white, etc., a little lower than the feldspar colors.

Extinction.—As the mineral is uniaxial, basal sections remain dark during rotation of stage. In all other sections extinction takes place and is parallel or symmetrical to cleavage lines when these appear.

Convergent Light: Basal sections show a broad cross, without rings. Optical character (—).

Alteration: Takes place easily to fibrous zeolites (natrolite), with stronger double refraction.

Differentiation: From other minerals by gelatinization test and staining with fuchsine. When present in small granules it is very difficult to distinguish from quartz or feldspar without this test. Quartz has stronger double refraction, does not show hexagonal outline and is optically (+). Feldspar is biaxial and often shows twinning.

* The minerals Nephelite, leucite, sodalite (haüynite and noselite) and melilite are often grouped together under the name "*feldspathoides*"; on account of their relations in rocks being equivalent to that of the feldspars.

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REMARKS: Nephelite bears the same relation to elæolite as sanidine does to orthoclase. It occurs only in the younger volcanic rocks; with sanidine in phonolite, with plagioclase in tephrite, without feldspar in nepheline-basalt, and with leucite in leucite-basalt. Elæolite occurs with orthoclase in elæolite-syenite, etc. Nephelite and elæolite frequently occur with the sodalite group. Nephelite gelatinizes with acids. H., 5.5 to 6. Sp. gr., 2.5 to 2.6.

TOURMALINE, Shorl.

ANISOTROPIC. UNIAXIAL. HEXAGONAL.

COMPOSITION: Uncertain, $R_{18}B_2(SiO_5)_4$. R chiefly Al, K, Mn, Ca, Mg, Li. $\dot{c} = \mathfrak{a}$. ELONGATION $\parallel \mathfrak{a}'$.

Usual Appearance in Sections: Staff-like individuals, bunched or in radiating aggregates, Fig. 33 B, or columnar crystals, Fig. 33 A.

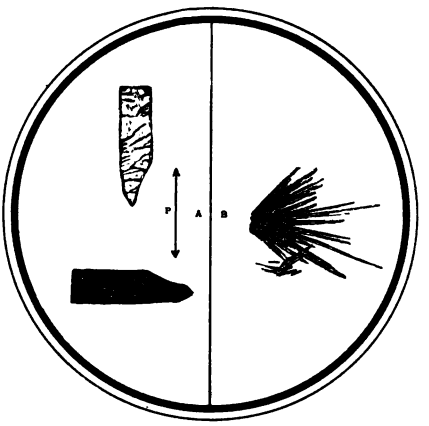

FIG. 33.—*A* Tourmaline, showing strong absorption at right angles to direction of elongation (*P* = plane of vibration of polarizer); *Quartzite*, Black Hills, D. *B* Tourmaline in radiate aggregate; *Granite*, Cornwall.

Color.—Varies greatly, grayish-blue, brown and black most common. Zonal structure may be indicated by differences in color.

Index of Refraction.—$n' = 1.636$.

Relief.—Noticeable against the colorless rock constituents, and surface rough.

Cleavage.—Not seen in thin sections, but irregular, transverse and longitudinal cracks may appear.

Polarized Light:

Pleochroism.—Distinct, even in light colored varieties, increasing with the depth of color. The greatest absorption takes place at right angles to the direction of elongation of the crystal, Fig. 33 A.

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The other minerals having this very strong absorption are hornblende, dark colored mica (distinguished by cleavage and lamella form) and allanite.

Crossed Nicols:

Double Refraction.—Quite strong ($\gamma - a = 0.02$).

Interference Colors.—Bright upper 1st or lower 2d order. May be masked by the strong absorption.

Extinction.—As tourmaline is uniaxial, basal sections remain dark during rotation of stage. In all other sections extinction is parallel to $\dot{c}$ axis.

Convergent Light: Cross-sections show a sharp cross. Optical character (—).

Alteration: Does not take place.

Differentiation: From HORNBLENDE.—By absence of cleavage, and by the fact that the greatest absorption takes place at right angles to the longitudinal axis, while in hornblende it takes place approximately parallel to the longitudinal axis, or to the cleavage lines which are parallel to this axis.

REMARKS: Found in granites, etc., also in metamorphic rocks near igneous intrusions. Tourmaline is not acted on by acids. H., 7 to 7.5. Sp. gr., 3 to 3.2. It can be separated from powdered rock by sp. gr. solutions combined with magnetic methods.

ANDALUSITE.

ANISOTROPIC. BIAXIAL. ORTHORHOMBIC.

COMPOSITION: $Al(AlO)SiO_4$. $\dot{c} = a$. ELONGATION $\parallel a'$.

Usual Appearance in Sections: More or less idiomorphic prismatic crystals Colorless or at times reddish. *Relief* medium (n' 1.638). Cleavage, parallel to almost square prism, may show. Pleochroism only marked in colored varieties, being reddish $\parallel \dot{c}$ (the direction of elongation or cleavage). Pleochoric halos may surround inclusions.

Crossed Nicols: Double refraction weak ($\gamma - a = 0.011$). Interference colors middle 1st order, white to yellow. ***Extinction*** parallel to $\dot{c}$ axis in longitudinal sections, symmetrical in cross sections. In *convergent light* axial angle very large; optical character (—).

Alteration: May occur (through atmospheric agencies), forming laminated and fibrous aggregates.

Differentiation:

(*a*) From SILLIMANITE by much weaker double refraction, less elongated crystals nd by elongation $\parallel a'$ (Sillimanite elong. $\parallel c'$).

(*b*) From DIOPSIDE by weaker double refraction and absence of extinction angles.

REMARKS: Very characteristic of metamorphic schists and of contact zones of clay slates with granite, etc. It is insoluble in hydrochloric acid. H., 7 to 7.5. Sp. gr., 3 18.

Chiastolite.—Occurs in same forms as macroscopic specimens, with characteristic arrangement of carbonaceous inclusions.

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SILLIMANITE, Fibrolite.

ANISOTROPIC. BIAXIAL. ORTHORHOMBIC.

COMPOSITION: $Al(AlO)SiO_4$. $c = c$. ELONGATION $\| c'$.

Usual Appearance in Sections: Long, slender, colorless prisms or needles; often in felt-like aggregates. *Relief* distinct ($n' = 1.667$). Transverse fractures common.

Crossed Nicols: Double refraction rather strong ($\gamma - a = 0.021$). Interference colors upper 1st or lower 2d order, red, purple, blue, etc. *Extinction* parallel to prisms. Optical character (+).

Differentiation:

(a) From APATITE by higher order interference colors and by elongation $\| c'$ (apatite has elongation $\| a'$).

(b) From ANDALUSITE, see under the latter mineral.

REMARKS: Found especially in gneisses and schists, often occurring with iolite (cordierite). It is insoluble in hydrochloric acid. H., 6 to 7. Sp. gr., 3.24.

TOPAZ.

ANISOTROPIC. BIAXIAL. ORTHORHOMBIC.

COMPOSITION: $Al(Al(O.F_2))SiO_4$. $c = c$.

Usual Appearance in Sections: Colorless crystals of short prismatic habit, rarely allotriomorphic. *Relief* medium ($n' = 1.615$), about the same as that of calcite. Cleavage perfect, parallel to base. Fluid inclusions abundant, also plates of hematite and ilmenite.

Crossed Nicols: Double refraction weak ($\gamma - a = 0.010$), about the same as that of quartz. Interference colors middle 1st order, white, yellow, etc. *Extinction* parallel to cleavage. In *convergent light* axial angle large; interference figure obtained from basal sections (*i. e.*, from sections showing no cleavage); optical character (+).

Alteration: May take place to kaolin or muscovite, by loss of F and taking up of H_2O and alkalies.

Differentiation: From QUARTZ by cleavage and biaxial character.

REMARKS: Common in greisen and all granitic rocks containing tin ore. It is insoluble in hydrochloric acid. H., 8. Sp. gr., 3.5.

STAUROLITE.

ANISOTROPIC. BIAXIAL. ORTHORHOMBIC.

COMPOSITION: $Fe(AlO)_4(AlOH)(SiO_4)_2$, but varying, may contain Mg or Mn. $c = c$. ELONGATION $\| c'$.

Usual Appearance in Sections: Short prisms, which may be twinned at 90° or 60°, or grains. Color yellowish to reddish-brown. *Relief* rather high and surface rough ($n' = 1.741$). Cleavage, both prismatic and pinacoidal, variable. Inclusions of minute quartz grains and carbonaceous matter found in larger crystals, but not in microscopic crystals. Pleochroism distinct but not strong, showing the darker color $\| c$ (direction of elongation.)

Crossed Nicols: Double refraction weak ($\gamma - a = 0.010$). Interference colors middle 1st order, white to yellow, etc. (about like quartz). *Extinction* parallel or symmetrical to cleavages or crystal outline. In *convergent light* axial angle large; optical character (+).

Alteration: Rarely takes place.

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Differentiation: From TITANITE, see under the latter mineral.

REMARKS: Found in metamorphic schists, associated with cyanite (disthene), iolite (cordierite), andalusite, etc. It is one of the minerals produced by thermal metamorphism, hence found in rocks of granite contact-zones. It does not occur in the eruptive rocks or in schists rich in amphibole. Staurolite is not acted on by hydrochloric acid. H., 7 to 7.5. Sp. gr., 3.4 to 3.8.

THE ORTHORHOMBIC PYROXENES.

Enstatite and Hypersthene.

ANISOTROPIC. BIAXIAL. ORTHORHOMBIC.

COMPOSITION: $(Mg.Fe)SiO_3$. $\dot{c} = \mathfrak{c}$. ELONGATION $\| \mathfrak{c}'$.

Enstatite contains little, if any, Fe. Hypersthene contains more Fe, its optical characters beginning to show with about 10%.

Usual Appearance in Sections: Allotrimorphic, seldom idiomorphic (prismatic). Columnar or fibrous structure $\| \dot{c}$ characteristic of allotrimorphic occurrences, Fig. 34. Prism angle about 92°. Outline of crystal sections very similar to that of monoclinic pyroxenes.

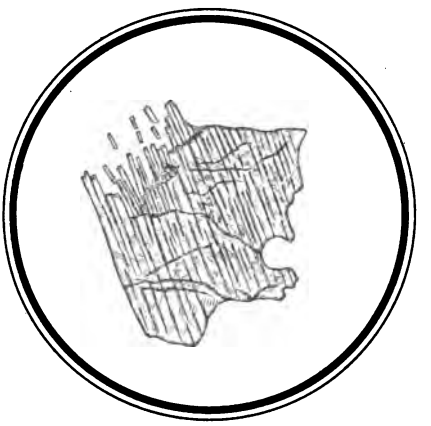

FIG. 34.—Enstatite, showing columnar or fibrous structure $\| \dot{c}$ axis; *Norite*, Harzburg.

Twinning.—Not so common as in monoclinic pyroxenes. Parallel growths of E. with monoclinic pyroxene (diallage) occur.

Color.—Varies with Fe %, E. colorless, H. brownish or greenish.

Index of Refraction.—$n' = 1.665$ to 1.700 (about the same as in monoclinic pyroxene).

Relief.—Marked and surface rough.

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Cleavage.—Fairly perfect parallel to brachy pinacoid $\infty\breve{P}\infty$(010); also rather imperfect parallel to prism (angle 92°), common to all pyroxenes. Imperfect parting parallel to macro pinacoid $\infty\bar{P}\infty$ (100) may occur.*

Inclusions.—Metallic or sub-metallic scales (generally brownish) very common in some varieties, giving a metallic sheen or bronzy lustre to principal cleavage face, *i. e.*, producing "schiller structure,"† Fig. 15. Iron ores also common as inclusions, often in elongated cylindrical forms.

Polarized Light:

Pleochroism.—Absent in E., but distinct in H., increasing with Fe %. The change in color may be very marked, from brownish red to greenish $\parallel \dot{c}$.

Crossed Nicols:

Double Refraction.—Weak, much weaker than in the monoclinic pyroxenes, increasing with Fe %. ($\gamma - \alpha = 0.009$ to 0.013).

Interference Colors.—Higher 1st order, about the same as quartz.

Extinction.—Parallel to cleavages, both pinacoidal and longitudinal prismatic, and bisecting angles of intersecting prismatic cleavages.

Convergent Light: Axial plane parallel to brachy pinacoid $\infty\breve{P}\infty$ (010), *i. e.*, parallel to best cleavage. Axial angles large ($2E = 95°$ to $> 180°$). Optical character for E. (+), for H. (−). On account of weak double reflection the interference figures are not very marked.

Alteration: Takes place to bastite, serpentine, etc. H. withstands decomposition better than E.

Differentiation: From the MONOCLINIC PYROXENES and AMPHIBOLE.—See under the latter.

REMARKS: Found in norite, gabbro, peridotite, porphyrite, andesite, basalts, etc. These minerals are in general not attacked by acids. H., 5 to 6. Sp. gr., 3.1 to 3.5. *Bronzite* is the name given to the variety containing about 5 % Fe and having the characteristic bronzy lustre due to inclusions.

Bastite (an alteration product of the othorhombic pyroxenes poor in Fe).—Composed of fibres, often traversed by irregular cracks. Color light yellowish or greenish and index of refraction about the same as Canada balsam. Pleochroism faint (only seen in thick sections), the greatest absorption taking place parallel to the fibres. Double refraction weak and extinction parallel to the fibres.

* The pinacoidal partings probably correspond in some cases to gliding planes.

† See p. 18.

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Axial angle large and axial plane at right angles to principal cleavage face, $\infty P\breve{\infty}$ (010). The position of the axial plane is the surest distinction between bastite and the orthorhombic pyroxenes.

CHRYSOLITE, Olivine.

ANISOTROPIC. BIAXIAL. ORTHORHOMBIC.

COMPOSITION: $(Mg.Fe)_2SiO_4$. ELONGATION $\parallel \mathfrak{a}'$ or $\mathfrak{c}'$.

Usual Appearance in Sections: Idiomorphic, or in grains or granular aggregates. Longitudinal sections more or less lath-shaped, with pointed ends, Fig. 10. Outlines of crystals often rounded or corroded. Incipient forms of growth may occur, and also interpenetration twins.

Color.—Nearly colorless, may be reddish (with high Fe %).

Index of Refraction.—$n' = 1.679$.

Relief.—Marked and surface rough.

Cleavage.—Parallel to brachy pinacoid $\infty P\breve{\infty}$ (010), less distinct parallel to macro pinacoid $\infty P\bar{\infty}$ (100). Often only made visible by decomposition. An irregular fracturing also occurs, which increases with alteration into serpentine.

Inclusions.—The iron ores, etc., frequent.

Polarized Light:

Pleocroism.—In general none, but noticed in the reddish varieties.

Crossed Nicols:

Double Refraction.—Very strong ($\gamma - \alpha = 0.036$).

Interference Colors.—Rather high in order (2d or 3d), higher than the colors of augite.

Extinction.—Always parallel to cleavage cracks.

Convergent Light: Axial plane parallel to base 0 P (001), that is at right angles to general direction of elongation. Axial angles very large ($2E > 180°$). Optical character (+).

Alteration: Into serpentine very common.*

* The alteration starts from the surface and cracks, producing fibres of serpentine, which stand at right angles to the edges and cracks. As serpentinization proceeds, new cracks form, due to increase in volume, and the process may continue until a complete net of serpentine fibres is formed, replacing the chrysolite.

The process is often accompanied by the separating out of the iron-ores. When subsequent serpentinization of the meshes takes place the resulting serpentine may appear almost isotropic (*Harker's Petrology for Students*, p. 63, 1895). For other alteration processes, see *Iddings' Rosenbusch*, p. 216. 1889.

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Differentiation:

(*a*). From light-colored MONOCLINIC PYROXENES.—By absence of extinction angles, cleavage (the intersecting prismatic cleavages of augite being of equal distinctness) and stronger double refraction.

(*b*). From minerals of similar habit.—By test for gelatinization.

REMARKS: Found only in basic rocks, as peridotite, diabase, gabbro, norite, basalts, etc. When not too poor in Fe chrysolite becomes permanently red and pleochroic when strongly heated. Chrysolite is decomposed by hydrochloric and sulphuric acids, with separation of gelatinous silica. H., 6.5 to 7. Sp. gr., 3.3 to 3.4.

Hyalosiderite (a more ferruginous chrysolite) and *Fayalite* (Fe_2SiO_4) are reddish in sections, and common in the basic porphyritic eruptive rocks.

IOLITE, Cordierite, Dichroite.

ANISOTROPIC. BIAXIAL. ORTHORHOMBIC.

COMPOSITION: $Mg_3(Al.Fe)_6Si_8O_{28}$. $\dot{c}$ = a. ELONGATION ∥ a'.

Usual Appearance in Sections: Grains, more rarely pseudo-hexagonal prisms. Twinning may occur and some basal sections show penetration twins. Colorless, but may be bluish in thick sections. *Relief* low ($n' = 1.536$), like quartz. Cleavage very variable, parallel to brachy pinacoid $\infty P \bar{\infty}$ (010), especially noticeable when decomposition has taken place. Irregular cracks often seen filled with a yellowish substance. Inclusions of sillimanite, zircon, green spinel, etc., characteristic. Pleochroism usually not observed, but may be quite strong in thick sections from prism zone (yellowish-white ∥ $\dot{c}$ to blue). Pleochroic halos, surrounding inclusions, common and bright yellow in color.

Crossed Nicols: Double refraction weak ($\gamma - a = 0.007$ to 0.010), like quartz. Interference colors middle 1st order, white to yellow. *Extinction* parallel to cleavage cracks. In *convergent light* axial angle large (hyperbolas only seen without ellipses); optical character (+).

Alteration: Takes place readily, forming mica like decomposition products, the decomposition commencing along the crevices.

Differentiation: From QUARTZ by observation in convergent light, by presence of decomposition along the crevices and by pleochroism in thick sections. The section can also be treated with hydrofluosilicic acid, when the evaporated solution yields characteristic prismatic crystals of magnesium fluosilicate.

REMARKS: Found in gneiss, granite, granulite and in some volcanic rocks. It is often associated with garnet, biotite, sillimanite, spinel, etc. In a thick section heating to redness makes the pleochroism more distinct. Iolite is only slightly acted on by acids. H., 7 to 7.5. Sp. gr., 2.6. It is hard to make a mechanical separation from quartz, on account of similarity in sp. gr.

TALC.

ANISOTROPIC. ORTHORHOMBIC?

COMPOSITION: $H_2Mg_3(SiO_3)_4$. ELONGATION ∥ c'. (Pseudo-Hexagonal).

Usual Appearance in Sections: Colorless plates, elongated like rods, or more rarely with round to hexagonal outline. Arrangement in rosettes or felting common. *Relief* very low ($n' = 1.55$). Cleavage perfect parallel to base, like mica.

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Crossed Nicols: Double refraction very strong ($\gamma - a = 0.035$ to 0.050). Interference colors 3d order, like muscovite. *Extinction* parallel to basal cleavage lines. In *convergent light* axial angle small; optical character (—).

Differentiation: From MUSCOVITE (with which it is easily confused) by microchemical tests, proving absence of alkalies and Al; and often by the more aggregate structure of the talc. Also by smaller axial angle of scales in convergent light.

REMARKS: Found mainly in metamorphic schists. It is insoluble in hydrochloric acid. H., 1 to 1.5. Sp. gr., 2.6 to 2.8.

NATROLITE.

ANISOTROPIC. BIAXIAL. ORTHORHOMBIC.

COMPOSITION: $Na_2Al(AlO)(SiO_3)_3 + 2H_2O$. $c = c$. ELONGATION $\parallel c'$.

Usual Appearance in Sections: Aggregates of colorless, fibrous crystals, which may have sphærulitic structure showing a dark cross between crossed nicols. *Relief* none ($n' = 1.483$).

Crossed Nicols: Double refraction weak ($\gamma - a = 0.012$). Interference colors the middle 1st order (yellow, etc.), a little higher than those of quartz. *Extinction* parallel to fibres. Optical character (+).

REMARKS: Never a primary mineral in rocks, but found in igneous rocks filling amygdaloidal cavities, and also as a very common alteration product of sodalite, noselite, nephelite and acid plagioclases. It gelatinizes easily with hydrochloric acid. H., 5 to 5.5. Sp. gr., 2.2.

OTHER ZEOLITES.*

COMPOSITION: Hydrous silicates; Al,Ca and Na being the chief bases.

Usual Appearance in Sections: The form depends on the individual mineral species, but the majority appear in elongated crystals or fibres. They are all colorless and most of them have a small index of refraction, hence very low *relief* (prehnite has distinct relief).

Crossed Nicols: The double refraction is generally very weak (between that of nephelite and quartz), giving very low order interference colors (prehnite and thomsonite have strong double refraction).

REMARKS. The zeolites are always secondary minerals in rocks. They gelatinize with hydrochloric acid.

GYPSUM.

ANISOTROPIC. BIAXIAL. MONOCLINIC.

COMPOSITION: $CaSO_4 + 2H_2O$.

Usual Appearance in Sections: Colorless, allotriomorphic grains. *Relief* low ($n' = 1.524$). Cleavage parallel to $\infty\breve{P}\infty$ (010) gives abundant cracks, other cleavages may also be noticed.

Crossed Nicols: Double refraction weak ($\gamma - a = 0.009$), the same as quartz. Interference colors middle 1st order, white to yellow. *Extinction* parallel to most perfect cleavage cracks; large extinction angles noticed with references to less perfect cleavages. In *convergent light* axial plane parallel to most distinct cleavages; optical character (+).

REMARKS: Forms a rock by itself, often associated with rock-salt. It also occurs in sedimentary anhydrite. Gypsum is soluble in hydrochloric acid. H., 1.5 to 2. Sp. gr., 2 2 to 2.4.

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* Analcite is isotropic, but often shows optical anomalies. It occurs in isometric crystals or allotriomorphic, and may be distinguished from leucite by gelatinizing with acids and by micro-chemical tests.

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MONOCLINIC PYROXENES, Augite, etc.

Including the monoclinic minerals of the Pyroxene family, which show distinctly the characteristic cleavage parallel to an almost right-angled prism.

ANISOTROPIC. BIAXIAL. MONOCLINIC.

ELONGATION || c'.*

COMPOSITION: $RSiO_3$, R = Ca, Mg, Mn, Fe, Al chiefly, with the Ca predominating over the Mg.

Usual Appearance in Sections: Both idiomorphic and allotriomorphic, Figs. 5 and 12, the habit varying with the chemical composition as follows:

Diopside (Ca, Mg varieties), long columnar crystals and grains.

Augite (ditto, but containing also Al and Fe), short prismatic crystals and grains.

Diallage, lamella (|| $\infty P\bar{\infty}$ (100)) or granular, generally showing fibrous structure || $\dot{c}$.

Prism angle = 87° 6′ (important in cross-sections). Sections of crystals nearly at right angles to the vertical $\dot{c}$ axis are octagonal or square with truncated corners, Fig. 5, while those parallel to the $\dot{c}$ axis are lath-shaped. Pyroxene also occurs in skeleton crystals and acicular microlites in eruptive rocks, and in some basalts the crystals have the "hour-glass" structure.

Zonal structure (especially in augites) may be marked by differences in color or extinction.

Twinning.—Common, usually the twining plane being the orthopinacoid $\infty P\bar{\infty}$ (100). Twin lamellæ may also be noticed within the crystal. Intergrowths occur with orthorhombic pyroxene and amphibole.

Color.—From almost colorless through green (diopsides, etc.) to brown (augites); may even be violet when the color appears to indicate Ti.

Index of Refraction.—n' = 1.68 to 1.72.

Relief.—High and surface rough.

Cleavage.—More or less perfect parallel to prism of 87° 06′. Cleavage cracks distinct and numerous, but not generally running uninterruptedly through crystal, Fig. 5. Cleavage not so perfect as that of amphibole.

* May be difficult to determine in the case of prism zone sections, showing large extinction angles.

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Parting.—Diallage has distinct parting parallel to ortho pinacoid $\infty P \bar{\infty}$ (100). Some pyroxene crystals may show parting parallel to base 0 P (001).

Inclusions.—Tabular microscopic interpositions, similar to those in bronzite, may occur in diallage. The iron-ores, apatite, etc., may occur in augite.

Polarized Light:

Pleochroism.—Usually feeble, and in general only appearing as different shades of the same color.

Crossed Nicols:

Double Refraction.—Strong ($\gamma - a = 0.021$ to 0.030), being stronger in the pale or colorless pyroxenes.

Interferencc Colors.—2d order, hence always bright tints.

Extinction.—Symmetrical in sections showing intersecting cleavage lines, in such cases bisecting the angles of the cleavage. In sections showing parallel cleavage lines, only parallel in ortho pinacoid $\infty P \bar{\infty}$ (100) sections, in all other sections an extinction angle being observed. The maximum extinction angle is large, lies in the obtuse angle, varies with the chemical composition from 36° 30′ to54°, and is only obtained when the section of the crystal is parallel to the clino pinacoid $\infty P \breve{\infty}$ (010), varying from this angle to 0°, when the section is parallel to the ortho pinacoid $\infty P \bar{\infty}$ (100).

Convergent Light: Axial plane parallel to clino pinacoid $\infty P \breve{\infty}$ (010). A cleavage flake parallel to ortho pinacoid $\infty P \bar{\infty}$ (100) shows the emergence of an optic axis (orthorhombic pyroxene would show emergence of a bisectrix). Axial angles large ($2E = 70°$ to 112°). Optical character (+). The interference figures are distinct on account of the strong double refraction.

Alteration: May take place to chlorite, serpentine or amphibole (uralitization*), depending on the chemical composition and the conditions producing the change.

Differentiation:

(*a*) From the ORTHORHOMBIC PYROXENES.—By extinction angle, the orthorhombic pyroxenes having always parallel extinction, and by higher order interference colors. Also from hypersthene by absence of, or much fainter, pleochroism. Diallage and bronzite might be confused on account of pronounced pinacoidal parting, fibrous structure and inclusions; but may be distinguished by the presence or absence of extinction angles and also by the position of the optic axes, relative to the best cleavage plates.

* See p. 64.

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(*b*) From AMPHIBOLE.—See under amphibole.

(*c*) From EPIDOTE.—When light colored and granular, by examination in convergent light. The plane of the optic axes is parallel to the longitudinal axis and cleavage cracks, while in epidote it is at right angles to these directions.

REMARKS: Next to the feldspars pyroxene is the most common constituent of the igneous rocks. Augite is found in eruptive rocks, diabase, melaphyre, augite-andesite, basalt, etc.; also in plutonic rocks. Diallage is common in gabbros, etc. Diopside varieties are found in crystalline schists, eclogite, etc. The green pyroxene (omphacite) is associated in eclogite with a green amphibole (smaragdite).

Chemical corrosion and mechanical deformation may occur; but the latter is rare, as, under the effects of dynamic metamorphism, the pyroxene changes to amphibole (uralitization). The green and yellow augites when heated to redness on platinum foil may become red in color. In general the pyroxenes are not attacked by acids. H., 5 to 6. Sp. gr., 3.3 to 3.5. The sp. gr. of the pyroxenes is considerably higher than that of the amphiboles of similar composition, hence mechanical separations are possible.

Acmite (*Ægirine*) (Na pyroxenes).—Occur in green or brown, elongated prismatic crystals, often not very transparent and with marked pleochroism (like amphibole). Zonal coloring is common. The elongation is $\parallel \mathfrak{a}'$ (distinction from amphibole whose elongation is $\parallel \mathfrak{c}'$). The index of refraction is higher than in the other pyroxenes ($n' = 1.80$) and the double refraction stronger ($\gamma - \alpha = 0.52$). The *extinction* angle lies in the acute angle and is small (5°), and the optical character (—).

These pyroxenes are only found in the eruptive rocks rich in alkalies, as elæolite-syenite, phonolite, certain trachytes, etc.; hence are associated with elæolite, sodalite, leucite, etc.

The term *Ægirine-augite* may be used to describe a soda, pleochroic augite with a large extinction angle (Weinschenk).

AMPHIBOLE, Hornblende, etc.

ANISOTROPIC. BIAXIAL. MONOCLINIC.

ELONGATION $\parallel \mathfrak{c}'$.

COMPOSITION: $R_4(SiO_3)_4$. R = Mg, Ca, Fe chiefly, also may contain Al, Na, Mn. The Mg predominates over the Ca.

Usual Appearance in Sections: Both idiomorphic and allotriomorphic, Fig. 35, the habit varying with the chemical composition as follows:

Tremolite (Mg_3Ca variety), long rods and columnar masses.

Actinolite ($(MgFe)_3Ca$ varieties), long rods, blades and fibres.

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Hornblende (Aluminous varieties), more or less elongated prisms.

Terminal faces are generally lacking in the above varieties, the crystals being jagged or frayed out. The ferruginous, basaltic hornblende is usually in well developed crystals with terminations; or, when corroded, surrounded by a dark rim of microlitic augites and iron ore grains ("resorption border").

Crystals are simple in form of prismatic habit, with prism angle 124° 30′. Cross-sections are acutely rhombic, generally with acute angles truncated, hence six-sided, Fig. 35 A (pyroxene being eight-sided). Longitudinal sections are lath-shaped and fibrous structure may be noticed. Crystals are less often microlitic than in the case of pyroxene.

Zonal structure occurs in the brown ferruginous hornblende.

Twinning.—Frequent, parallel to ortho pinacoid $\infty P\bar{\infty}$ (100). Twins dual, less often multiple. Intergrowths with pyroxene and biotite occur.

Color.—From colorless (tremolite), though green (actinolite and common hornblende) to brown (basaltic hornblende).

Index of Refraction.—$n' = 1.621$ to 1.642 (higher in the ferruginous hornblende).

Relief.—Distinct, but not so marked as in pyroxene.

Cleavage.—Perfect, parallel to prism of 124° 30′. Generally appears in thin sections as sharp cracks crowded close together, Fig. 35. More perfect than in pyroxene.

Some of the long prisms (actinolite and tremolite) may show parting at right angles to $\dot{c}$ axis.

Inclusions.—The iron-ores, apatite, etc., may be found in hornblende. At times the iron-ores are so abundant as almost to form a pseudomorph after the amphibole.

Polarized Light:

Pleochroism.—All colored amphiboles show pleochroism, which is stronger the darker the color of the variety. The absorption is very marked, being greatest in the general direction of the cleavage lines in longitudinal sections, Fig. 35 B. Marked differences in absorption are also characteristic of the mineral species biotite, tourmaline and allanite.

Crossed Nicols:

Double Refraction.—Quite strong, but a little weaker than in pyroxene ($\gamma - \alpha = 0.019$ to 0.027). Ferruginous, basaltic hornblende has stronger double refraction.

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Interference Colors.—2d order, hence bright tints. May be masked by the strong absorption.

Extinction.—Always symmetrical in sections showing intersecting cleavage lines, in such cases bisecting the angles of the cleavage. In sections showing parallel cleavage lines, only parallel in ortho pinacoid $\infty P\bar{\infty}$(100) sections, in all other sections an extinction angle being observed. The maximum extinction angle lies in the acute angle and is much smaller than in pyroxene, varying with the chemical composition from 0°–20°. In common hornblende,

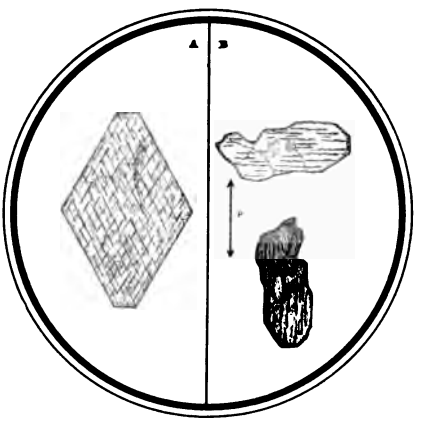

FIG. 35.—Amphibole. *A* Section ⊥ *c* axis, showing intersecting prismatic cleavages. *B* Sections approximately ‖ *c* axis, showing parallel cleavages and strong absorption parallel to direction of elongation and cleavage (*P* = plane of vibration of polarizer). *Hornblende Schist*, Peekskill, N. Y.

actinolite and tremolite 15°–18°; in the basaltic hornblendes 0°–10°. The maximum extinction angle is only obtained when the section of the crystal is parallel to the clino pinacoid $\infty P\bar{\infty}$ (010), varying from this angle to 0°, when the section is parallel to the ortho pinacoid $\infty P\bar{\infty}$ (100).

Convergent Light: Axial plane parallel to clino pinacoid $\infty P\bar{\infty}$ (010). Axial angles large ($2E = 77°$, etc.) Optical character (—).

Alteration: May take place to talc, serpentine, chlorite, asbestus, etc., depending on the chemical composition. Amphibole frays out and becomes fibrous during alteration, and may also lose color.

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Differentiation:

(*a*) From PYROXENE.—By much stronger pleochroism, and by cleavage and extinction angle. In pyroxene the cleavage (parallel to prism of 87° 06′) is less perfect; and the extinction angle is much larger, varying from 36° to 54°.

(*b*) From BIOTITE.—By the extinction in the mica being always about parallel to the cleavage. Both have strong absorption, but biotite shows very slight pleochroism in sections parallel to the cleavage, and has only the one cleavage parallel to the base.

Colorless tremolite may be distinguished from muscovite and talc by extinction angles, relief and lower order interference colors.

(*c*) From TOURMALINE.—By presence of cleavage, and by the fact that absorption is most marked about parallel to the elongation (also to parallel cleavage lines), while in tourmaline the absorption is strongest at right angles to the elongation.

(*d*) From the ORTHORHOMBIC PYROXENES.—By extinction angles, the latter having parallel extinction, and by prismatic cleavage of 124° 30′. Pleochroism is strong in the colored varieties of both species, but in amphibole it appears more generally as a variation of the same color; while in hypersthene a change in color is often noticed, from brownish red to greenish parallel to $\dot{c}$ axis.

REMARKS: Amphibole comes next to pyroxene in importance and distribution of the dark colored ferruginous rock forming minerals. As a rule it occurs in rocks with a large percentage of SiO_2, associated with quartz and orthoclase; while augite generally occurs in rocks of a basic nature, associated with plagioclase and little or no free SiO_2. Hornblende is found in syenite (brown and green), diorite (green), trachyte and andesite (brown), etc. Common green hornblende is often secondary, being derived from augite. Actinolite varieties (green) are found in amphibolite, metamorphic schists, etc.; frequently secondary (see uralite) in gabbro, diabase, etc. Tremolite (white) occurs as a contact mineral in limestones, etc.

The hornblende crystals in eruptive rocks, being among the first formed constituents, have often suffered subsequent corrosion by the magma, giving rise to the dark border already mentioned. Mechanical deformations are found in massive and schistose rocks. Light green amphiboles, with weak pleochroism, may often be colored intensely red and made strongly pleochroic by heating to redness on platinum foil. In genera, the amphiboles are not affected by acids. H., 5 to 6. Sp. gr., 2.9 to 3.3.

Glaucophane (Na amphibole).—Blue in color, with striking pleochroism and small extinction angle (5°). It occurs in prisms in metamorphic schists.

Uralite.—Pyroxene altered to amphibole, having the outward crystal form of pyroxene and the physical characters and cleavage of amphibole. The change usually commences on the surface and the uralite does not form a single compact crystal, but con-

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sists of numerous slender columns parallel to one another. These little columns or fibres have their $\dot{c}$ and $\bar{b}$ axes parallel to the positions of these axes in the parent mineral. The color is green and the pleochroism weak to strong.

This change is called "*uralitization*" and commonly results from dynamic metamorphism. When the alteration is not complete, portions of the original pyroxene may be left, having all the characteristic optical properties of this latter mineral.

MICA GROUP.

ANISOTROPIC. BIAXIAL. MONOCLINIC.

May appear hexagonal or orthorhombic.

COMPOSITION: ELONGATION (|| cleavage) || $\mathfrak{c}'$.

Biotite (black or ferro-magnesium mica) = $(H.K)_2(Mg.Fe)_2Al_2(SiO_4)_3$, approx.

Phlogopite = a magnesium mica, near biotite, but containing little Fe.

Muscovite (white or potash mica) = $H_2(K.Na)Al_3(SiO_4)_3$, with some replacement by Mg or Fe.

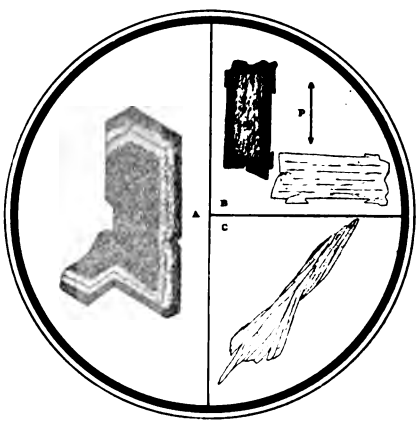

FIG. 36.—Mica. *A* Biotite, showing hexagonal cross-section and zonal markings; *Minette*, Freiberg. *B* Biotite, showing strong absorption parallel to cleavage and also zonal marking (*P* = plane of vibration of polarizer); *Minette*, Cumberland. *C* Muscovite in bent shreds in gneiss.

Usual Appearance in Sections: Scales, which may be notched or jagged, with lateral sections lath-shaped; or shreds, Fig. 36 C. When distinctly crystallized (black micas) the thin hexagonal

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plates have plane angles of 120°, Fig. 36 A. Micas of different kinds often associated together in parallel position, also intergrown with hornblende.

Zonal structure not uncommon in the dark micas, Fig. 36 A, which may also have dark border like hornblende.

Color.—Depends on chemical composition. Biotites, brown, green or red to almost opaque. Phlogopites, light yellowish-brown. Muscovites colorless.

Index of Refraction.—$n' = 1.584$ to 1.598.

Relief.—Low and surface smooth. Biotite has more marked relief.

Cleavage.—Very perfect, parallel to base 0 P (001), Fig. 11. Basal sections show no cleavage, but all other sections show many sharp, parallel cleavage cracks.

For percussion and pressure figures, see reference given below.*

Inclusions.—May be arranged parallel to lines of pressure figure. Rutile needles, tourmaline, apatite, etc., common in black mica. Zircon inclusions often surrounded by pleochroic halos.

Polarized Light:

Pleochroism.—Varies with the color, being very marked in the colored varieties (from pale yellow to chestnut-brown or black). The strong absortion, about parallel to the cleavage lines, is very characteristic of the colored micas, Fig. 36 B. Strong absorption is also noticed in hornblende, tourmaline and allanite. Absorption may even be noticed around inclusions (pleochroic halos) in colorless, non-pleochroic micas. Cleavage plates of biotite are only slightly pleochroic on account of the approximate uniaxial character.

Crossed Nicols:

Double Refraction.—Very strong ($\gamma - \alpha = 0.040$ to 0.044).

Interference Colors.—High order (3rd). May be very brilliant in thin sections of the colorless micas, which often appear iridescent. The strong absorption of the colored micas may mask the interference colors.

Extinction.—About parallel to cleavage lines. Very small extinction angles may be noticed in biotites. Basal sections of biotite (the approximately hexagonal mica) usually appear isotropic.

Convergent Light: Axial plane† at right angles to basal

* *Iddings' Rosenbusch*, p. 256.

† Depending on whether the axial plane is parallel, or at right angles to the clino pinacoid $\infty P \breve{\infty}$ (010) (the plane of symmetry), we have micas of the 2d or 1st order.

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cleavage; therefore cleavage plates always show well defined interference figures, generally biaxial in character. The axial angles vary greatly, being usually small for biotite (may appear uniaxial) and large for muscovite. Optical character for all micas (—).

Alteration: Biotites decompose quite easily, lose color and may become completely bleached, which appears to be due to a leaching out of the iron. May also alter to green chlorite, with a fraying out of the mica and a change to chloritic structure.

Phlogopites may alter to fibrous, scaly masses, apparently chiefly talc.

Muscovites are characterized by their freshness, and do not seem to suffer from weathering.

Differentiation:

(*a*) From HORNBLENDE.—Black mica has extinction about parallel to the cleavage, while hornblende may have extinction angles of from 0° to 20°. Both have strong absorption, but biotite shows very slight pleochroism in basal sections, which also give approximately uniaxial interference figures in convergent light.

(*b*) From TOURMALINE.—Black mica shreds show absorption parallel to elongation, while in tourmaline the absorption is at right angles to elongation. There is also an absence of cleavage in tourmaline.

(*c*) From CHLORITE.—By strong double refraction, the high order colors, however, being often masked in the colored micas. Chlorite also shows aggregate structure and is almost always greenish in color.

(*d*) From TALC.—White mica by large axial angle of scales in convergent light and by micro-chemical tests. The distinction may be very difficult.

REMARKS: Muscovite is frequent in granite, gneiss, mica schists, phyllites, etc. Biotite is found in granite and is common in eruptive rocks (which is not the case with muscovite), as trachyte, andesite, etc., also occurs in some basalts. In the eruptive rocks it is one of the oldest secretions, formed immediately after the iron-ores, zircon and apatite. Phlogopite generally occurs in crystalline limestone and serpentine. Chemical corrosion occurs in original biotite of porphyritic rocks, producing a "resorption border" of augite and magnetite. Mechanical deformations, producing bending and slipping along "gliding" planes, are common to all varieties of mica. The muscovites, together with the feldspars, are the most characteristic minerals of dynamo metamorphic origin. Biotites and phlogopites are attacked by sulphuric acid at high temperatures. Muscovite is but slightly attacked by acids. H., 2 to 3. Sp. gr., 2.7 to 3.2. The specific gravity separation between the micas is difficult on account of the scaly nature of the minerals.

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Other micas occur, some being alteration products of those already described. Among these may be mentioned:

Lepidolite (Li mica).—Colorless, found in granitic veins.

Damourite (*Sericite*) (hydrous K mica).—Usually colorless, scaly aggregates with fibrous structure.

CHLORITE.

Embracing the members of the Chlorite Group, commonly occurring in rocks.

ANISOTROPIC. BIAXIAL. MONOCLINIC?

The minerals of this group usually appear uniaxial, and crystallize in part with hexagonal symmetry.

COMPOSITION: May be considered as isomorphous mixtures of $H_4(MgFe)_3Si_2O_9$ and $H_4(MgFe)_2(AlFe)_2SiO_9$ (Rosenbusch).

Usual Appearance in Sections: Aggregates of small, flat scales of irregular outline, with parallel, laminated structure. May also occur with fibrous structure, parallel or sphærulitic; or in minute grains as a pigment in other minerals.

Color.—Generally green, varying from greenish white to dark green.

Index of Refraction.—$n' = 1.577$.

Relief.—None.

Cleavage.—Like mica, very perfect; parallel to flat face, which is considered to be the basal plane. This cleavage may not be noticed, especially in fibrous or secondary chlorite in rocks.

Polarized Light:

Pleochroism.—In green and yellow tints (green || cleavage), being more marked in dark colored varieties. Basal sections are non pleochroic, the mineral being practically uniaxial.

Crossed Nicols:

Double Refraction.—Very weak ($\gamma - \alpha = 0.001$ to 0.005).

Interference Colors.—Very low 1st order, gray, bluish-gray, berlin-blue, etc. At times may be scarcely noticed.

Extinction.—Plates parallel to cleavage generally appear isotropic or only show faint illumination. In other sections extinction is apparently parallel to the cleavage. Complete extinction may not take place, due to aggregate structure.

Convergent Light: Plates parallel to cleavage show, at times, an indistinct interference cross, which may open into two hyperbolas, indicating biaxial nature of crystallization. Optical character ($\pm$).

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Differentiation: From SERPENTINE.—By being generally more pleochroic, but the distinction between these two minerals may be very difficult. Chlorite may resemble decomposed or green mica (mica has, however, strong double refraction). The different species in the chlorite group cannot usually be distinguished in rocks.

REMARKS: Found in chlorite schists, and as a secondary mineral in eruptive and metamorphic rocks, resulting from the decomposition of black mica, amphibole, pyroxene, etc. Chlorites are acted on by hot hydrochloric acid, and decomposed easily by sulphuric acid. H., 2 to 3. Sp. gr., 2.6 to 2.96. A thin section heated to redness on platinum foil loses water and becomes opaque. Ferruginous varieties are turned reddish-brown to black by heating (serpentine, as it contains less iron, may give negative results with this test).

Delessite.—Has stronger relief and double refraction and is found in sphærulites, filling cavities in amydaloidal basic rocks.

EPIDOTE.

ANISOTROPIC. BIAXIAL. MONOCLINIC.

ELONGATION $\parallel \mathfrak{a}'$ or $\mathfrak{c}'$.

COMPOSITION: $Ca_2Al_2(AlOH)(SiO_4)_3$, with some Fe replacing Al.

Usual Appearance in Sections: Columns, more or less elongated parallel to ortho axis $\bar{b}$, or in irregular grains or aggregates.

Twinning.—May occur.

Color.—From almost colorless to yellow tints.

Index of Refraction.—$n' = 1.751$.

Relief.—High and surface rough.

Cleavage.—Parallel to base 0 P (001), imperfect parallel to ortho pinacoid $\infty P\bar{\infty}$ (100). Basal cleavage cracks not very numerous and appear parallel to general direction of elongation.

Cross parting may also be noticed.

Polarized Light:

Pleochroism.—Varies with the color, being faint in the light colored varieties. Not so strong as in hornblende. In crystals from Sulzbach it is very strong, green to colorless or light yellow $\perp \bar{b}$.

Crossed Nicols:

Double Refraction.—Variable, often very strong ($\gamma - \alpha = 0.038$ to 0.056).

Interference Colors.—High orders.

Extinction.—Parallel to cleavage in elongated sections. In other sections extinction angles may vary from 0° to 28°.

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Convergent Light: Axial plane at right angles to elongation of crystal. Axial angles very large ($2E < 180°$). Optical character (—).

Alteration: Does not take place readily by weathering.

Differentiation: From light colored MONOCLINIC PYROXENE.—By having plane of optic axes at right angles to principal cleavage cracks (running parallel to direction of elongation), while in pyroxene plane of optic axes is parallel to prismatic cleavage cracks.

REMARKS: Epidote is essentially a secondary mineral, resulting from the alteration of the feldspars and the ferro-magnesium silicates. It is found in crystalline schists (especially those containing hornblende), gabbro, diorite, diabase, lime-silicate hornstones, etc. Epidote is partially decomposed by hydrochloric acid. H., 6 to 7. Sp. gr., 3.32 to 3.45.

Piedmontite (containing Mn).—Red in color. Very pleochroic, red to yellow. Found in porphyrite of Scotland, the famous "Porfido rosso antico" of Egypt and in certain Japanese mica-schists.

ZOISITE.

Orthorhombic member of Epidote group.

COMPOSITION: Essentially the same as epidote without any Fe.

Usual Appearance in Sections: Colorless prisms or granular aggregates, showing no pleochroism. The cleavage is parallel to brachy pinacoid $\infty \breve{P}\infty$ (010), and the longer individuals show transverse parting.

Zoisite resembles epidote but is differentiated by its weak double refraction (grayish or whitish interference colors), always parallel extinction and optical character (+).

REMARKS: Occurs associated with epidote in altered basic igneous rocks and metamorphic schists.

TITANITE, Sphene.

ANISOTROPIC. BIAXIAL. MONOCLINIC.

COMPOSITION: $CaSiTiO_5$. ELONGATION $\| a'$.*

Usual Appearance in Sections: Wedge-shaped crystals when primary, Fig. 37, irregular grains when secondary. May be only translucent. Sections of crystals commonly acute rhombs or long lath-like shapes.

Twinning.—Occurs, the twinning boundary bisecting the acute angles of the rhomb (only noticed between crossed nicols).

Color.—Brownish, yellowish or colorless.

* Test not easily made on account of the very high order interference colors, resulting from the strong double refraction.

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Index of Refraction.—$n' = 1.93$.

Relief.—Very high and surface rough, the relief being more distinct than in the case of epidote.

Cleavage.—Imperfect parallel to prism, only appears as a few rough cracks. As the prism is not a predominant form the cleavage cracks are not parallel to any crystallographic boundary. Cleavage rarely observed in secondary grains.

FIG. 37.—Titanite crystal (in centre) and granular mixture of hornblende *h*, feldspar *f*, biotite *b*, pyroxene *p* and apatite *a*.

Polarized Light:

Pleochroism.—Varies with the color, being more distinct in colored crystals, yellowish (the lighter color) $\| a'$ and reddish-brown $\| c'$. Scarcely noticed when the color is light.

Crossed Nicols:

Double Refraction.—Very strong ($\gamma - \alpha = 0.121$).

Interference Colors.—Very high order, like those of calcite. Often no change from ordinary color of section is noticed when nicols are crossed.

Extinction.—Extinction angles not characteristic. There may be no complete extinction in white light, owing to the strong axial dispersion.

Convergent Light: On account of the very strong characteristic dispersion of the optic axes ($\rho > \upsilon$), the axial angle varies a good deal with the color of the light used, $2E_\rho = 54°$, $2E_\upsilon = 33°$. By using colored glasses this variation in the axial angle can be seen. The optical character is (+).

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Alteration: May take place.

Differentiation: From STAUROLITE.—In convergent light the axial plane is shown to be in the shorter diagonal of the cross-section, while in staurolite it is in the longer diagonal.

REMARKS: Titanite is found in syenite, diorite, trachyte, phonolite, amphibolite, etc. As a secondary product it is associated with ilmenite and rutile. It is partly soluble in hot hydrochloric acid and completely decomposed by sulphuric acid. H., 5 to 5.5. Sp. gr., 3.3 to 3.7. In a specific gravity separation, it falls with the ferruginous minerals (on account of its density), and from these can generally be separated by electro-magnetic methods.

FELDSPAR GROUP.

Orthoclase, Microcline and the Plagioclases.

ORTHOCLASE.

ANISOTROPIC. BIAXIAL. MONOCLINIC.

ELONGATION (|| cleavage) || a'.

COMPOSITION: $KAlSi_3O_8$, with some replacement by Na.

Usual Appearance in Sections; Both idiomorphic and allotriomorphic. In porphyritic rocks habit of crystals more or less tabular parallel to clino pinacoid $\infty P\bar{\infty}$ (010), or rectangular much extended parallel to clino axis *c*. Dimensions of crystals vary extremely; microlites occur, at times forming spærulitic structure.

Intergrowths with microcline and plagioclase common, forming "microperthite" when lamellæ are microscopic. Associated also with quartz,* forming "pegmatite" and "micro-pegmatite."

Zonal structure may be very marked,† Fig. 19.

Twinning.—Very common, generally after *Carlsbad* law, Fig. 17; the twinning boundary, dividing the section longitudinally, either being parallel to edges of crystal or bent or jagged. Twinning after *Baveno* (twinning boundary diagonal) and *Manebach* laws less common. ‡

Color.—Colorless, or tinged by oxide of iron.

Index of Refraction.— $n' = 1.523$.

Relief.—None and surface smooth.

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* See under quartz, p. 44.

† In the case of the plagioclases the kernel is basic and the zones become more acid towards the periphery, as shown by the characteristic extinction angles.

‡ *Iddings' Rosenbusch*, p. 278.

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Cleavage.—Perfect, parallel to base 0 P (001), and almost as perfect parallel to clino pinacoid $\infty P\bar{\infty}$ (010). Cleavage cracks usually only noticed in very thin sections. The two cleavages intersect at 90° in ortho zone sections. Cleavage not so distinct as that of mica, hornblende, etc.

Inclusions.—May be present and arranged in regular order, but not important. Do not occur in individuals of a second generation.

Polarized Light:

Pleochroism.—None.

Crossed Nicols:

Double Refraction.—Very weak ($\gamma - \alpha = 0.007$).

Interference Colors.—Lower 1st order, bluish-gray, white, etc., not quite so bright as colors of quartz and plagioclase.

Extinction.—The extinction angle on base 0 P (001), with reference to clino pinacoid $\infty P\bar{\infty}$ (010) cleavage cracks, is 0°. On clino pinacoid, with reference to basal cleavage cracks, it is 3°–7° (rarely 12°). Some sections (notably in glassy sanidine grains) may appear dark during complete rotation. This is due to the fact that the axial angle is very small and the sections act approximately like those of a uniaxial mineral at right angles to the optic axis.

Convergent Light:* Plane of optic axes in general at right angles to clino pinacoid $\infty P\bar{\infty}$ (010) (plane of symmetry); but in some sanidines parallel to plane of symmetry. Axial angles vary, $2E = 125°$ (orthoclase), 0°–50° (sanidine).† May appear uniaxial when axial angle is very small. Optical character (—).

Alteration: Leaching out of the potash produces an alteration into kaolin‡ or muscovite. The alteration generally commences along the cleavage cracks, and when it has progressed very far the whole feldspar appears opaque or cloudy, and no perceptible change takes place between crossed nicols. As this decomposition is very prevalent in many rocks, the orthoclase is rarely clear or pellucid. Epidote is often noticed as a result of the decomposition, when accessory solutions are present.

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*On account of the weak double refraction the interference figures are not very sharp or well defined in thin sections. In most cases only the black hyperbolas are seen without any colored curves.

†By heating feldspar crystals the axial angle decreases to 0° and then increases in the plane of symmetry (at right angles to its former position). On cooling the axial angle returns to its former position if the temperature has not exceeded 500° C. If the temperature has been 600°—1000° C. for some time the axial angle will not return to its former position. This fact may give some clue as to the temperature at which the feldspar crystals formed.

‡This change to kaolin in granite is called by Dolomieu "*La maladie du granit.*"

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Differentiation:

(*a*) From the other FELDSPARS.—See under the latter minerals.

(*b*) From QUARTZ.—Feldspar (notably sanidine) occurring in clear glassy grains, which appear uniaxial in convergent light, may resemble quartz. But when tested the optical character is (—), while that of quartz is (+).

REMARKS: Found as an essential constituent in the more acid plutonic and older volcanic rocks, as; granite, syenite, trachyte, porphyry, and also in gneiss, schists, etc. Chemical corrosion (producing rounded or looped grains), Fig. 7, and mechanical deformation (producing angular, sharp-edged, broken grains and undulatory extinction*), Fig. 8, occur in orthoclase. Orthoclase is practically insoluble in acids. H., 6 to 6.5. Sp. gr., 2.56.

Sanidine.—This clear, glassy variety of orthoclase, occurs in the later eruptive rocks, rhyolite, trachyte, obsidian, etc. Sanidine often has a parting parallel to ortho pinacoid $\infty P\bar{\infty}$ (100), which may be noticed in sections so thick that the cleavage is not seen. In general it shows no sign of decomposition, and has a smaller axial angle than orthoclase. Inclusions are more abundant than in orthoclase.

MICROCLINE.

ANISOTROPIC. BIAXIAL. TRICLINIC.

COMPOSITION: $KAlSi_3O_8$.

Usual Appearance in Sections: As a rock constituent in irregular grains. Grains scarcely ever simple individuals, but polysynthetic masses, twinned after *Albite* and *Pericline* laws, Fig. 18. Intergrowths with orthoclase and albite frequent.

The general characters and alteration are the same as with orthoclase.

Differentiation:

(*a*) From ORTHOCLASE.—Simple crystals (not showing crossed twinning) have an extinction angle of + 15° 30′ on the base 0 P (001), with reference to the brachy pinacoid $\infty P\bar{\infty}$ (010) cleavage; while in orthoclose the extinction angle is 0°.

(*b*) From all other FELDSPARS.—All sections, except those parallel to the brachy pinacoid $\infty P\bar{\infty}$ (010), show, between crossed nicols, the characteristic *gridiron* structure or crossed rectangular grating of microcline. The lamellæ are generally thinner than in the plagioclases and more "spindle-shaped."†

* See p. 24.

† Hatch's *Introduction to the Study of Petrology*, p. 33.

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REMARKS: Found with orthoclase, often almost replacing it, in granite, syenite, gneiss, etc. Formerly classed as orthoclase. A structure like the microcline twin structure may be produced in orthoclase by dynamic action.*

THE PLAGIOCLASES.

Albite, Oligoclase, Labradorite, Anorthite.

ANISOTROPIC. BIAXIAL. TRICLINIC.

ELONGATION (|| *Albite* twin lamellæ) || $\mathfrak{a}'$ (except in anorthite when it may be || $\mathfrak{a}'$ or $\mathfrak{c}'$).

COMPOSITION:†

Albite, $NaAlSi_3O_8$.

Oligoclase, $n\,(NaAlSi_3O_8) + CaAl_2Si_2O_8$, $n = 2$ to 6.

Labradorite, $NaAlSi_3O_8 + n\,(CaAl_2Si_2O_8)$, $n = 1$, 2 or 3.

Anorthite, $CaAl_2Si_2O_8$.

Usual Appearance in Sections: Much the same as orthoclase. Lath-shaped‡ forms and microlites very common, especially in the acid series.

Twinning.—Polysynthetic, after *Albite* law, very common; the twinning appearing between crossed nicols as a series of dark and light bands, bounded by parallel edges, Figs. 6 and 12. The twin lamellæ are parallel to brachy pinacoid $\infty P\breve{\infty}$ (010), hence not observed in sections parallel to this pinacoid. The lamellæ may appear irregular and interrupted, and seem to be broader in the basic than in the acid series. In some cases polysynthetic twinning, after both *Albite* and *Pericline* laws, may take place at the same time, giving rise to a structure somewhat similar to that of microcline. In addition the polysynthetic crystals may be twinned like orthoclase after *Carlsbad* and *Baveno* laws.

The general characters are the same as those of orthoclase with the following differences:

The *cleavages*, parallel to base 0 P (001) and brachy pinacoid $\infty P\breve{\infty}$ (010), never intersect at right angles, as is the case in ortho

* J. W. Judd, *Geol. Mag.* [3], Vol. VI., p. 243, 1889.

†The chemical composition of the feldspar group is rather complex; but the feldspars may be regarded as forming a series from the composition $R'AlSi_3O_8$ (in which R′ is either K or Na) to the composition $R''Al_2Si_2O_8$ (in which R″ is Ca), consisting for the most part of isomorphous mixtures of these types. The compositions of only a few of the common feldspars are given above.

‡ The lath-shaped feldspars, moulding the augite, give to diabases the so-called "ophitic" structure, Fig. 12. The peculiarity of this structure is that the feldspars crystallized before the augite, which is contrary to the usual order of formation.

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zone sections of orthoclase. This is due to the triclinic system of crystallization, but the divergence from a right angle is small (93° 36′ to 94° 10′).

Inclusions at times may be quite important, as the vitreous inclusions characteristic of oligoclase in andesites, etc., and the iron-ore inclusions and other microlites in labradorite. The arrangement of these inclusions may show the zonal growth of the crystals.

The *double refraction** is a little stronger than for orthoclase ($\gamma - \alpha = 0.007$–0.013), hence producing slightly brighter interference colors in sections of the same thickness.

General Rules Regarding Extinction Angles.

As these minerals are triclinic, *extinction* takes place in all sections unsymmetrically with respect to crystallographic, twinning or cleavage lines; hence extinction angles are always observed, although in many cases they are small.

Schuster's method of recognizing the different feldspars by extinction angles measured on the cleavage plates† is very precise, but not always applicable for crystals in rock sections.

Extinction Angles‡

On base measured from trace of pinacoidal cleavage.		On brachy pinacoid measured from trace of basal cleavage.	
Albite	+ 5°.	Albite	+ 20°.
Oligoclase	+ 1°.	Oligoclase	+ 5°.
Labradorite	− 9°.	Labradorite	− 24°.
Anorthite	− 37°.	Anorthite	− 37°

Confusion may here arise between albite and labradorite, but the more acid oligoclase is readily distinguished from the basic anorthite.

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* The strength of the double refraction decreases with an increase in the Ca%.

† For this method of investigation little cleavage flakes or plates can often be obtained from the crushed material. If a fragment with only one cleavage surface is obtained, it must be cemented to a glass by this surface and ground down to a thin section with parallel sides.

‡ By convention the angles on base and pinacoid are (+) when the direction of extinction has apparently moved, as the hands of a watch, with reference to the upper right hand edge (between base and pinacoid) of the crystal. When the reverse is true the angles are (−).

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The method of *Michel Lévy** and others is often applicable, especially in the two following cases:

(*a*) Sections showing *Albite* twinning.—Take sections as nearly perpendicular to the lamellæ as possible (these are known by the extinction angles on each side of the twin-line being approximately the same, and by the fact that "equal illumination," of the two adjacent lamellæ, is obtained when the twin-line is parallel to the plane of vibration of either nicol. Measure the extinction angles in three or four sections thus selected and take the maximum value.† This should be very close to the maximum extinction angle, which is a constant for each kind of feldspar.

MAXIMUM EXTINCTION ANGLES IN SECTIONS PERPENDICULAR TO ALBITE TWINS.

Albite,	18°.	Labradorite,	32°.
Oligoclase,	4°–12°.	Anorthite, over	37°.

(*b*) Microlites (assumed to have their length parallel to the intersection of the two principal cleavages).‡—Measure the extinction angles from the long axis and take the maximum angle obtained from several microlites.

MAXIMUM EXTINCTION ANGLES§ FROM LONG AXIS.

Albite,	20°.	Labradorite,	24°.
Oligoclase,	5°.	Anorthite,	37°.

Ambiguity may arise here also, but oligoclase and the more basic plagioclases (above 20°) are easily distinguished.‖

* For very exact methods of determination, see *Étude sur la Détermination des Feldspaths dans les Plaques Minces*, Michel Lévy, Paris, 1894; and *The Determination of the Feldspars*, N. H. Winchell, *Am. Geol.*, Vol. XXI., No. 1, 1898.

† This test is only possible when suitable sections of the given feldspar in the rock section can be found. The method, however, can be used with great accuracy with the aid of some form of apparatus for properly orienting the section. See "Klein's Apparatus for the Orientation of Thin Sections," *Sitzungsber. Berlin. Akad.*, 1895, 1151; (also in *N. Y. Acad. Sci.*, Vol. XVI., p. 51, 1897); and Von Federov's "Universal Table," *Zeit. fur Kryst., etc.*, Vol. XXV., p. 351.

‡ When they show *Albite* twinning, the previous method can be used.

§ These angles, as well as those previously given, are the extinction angles of characteristic feldspars of definite composition. As the composition varies through a long series, so the extinction angle changes, one being a function of the other.

For a complete list of compositions and related extinction angles, see *Iddings' Rosenbusch* and *Lévy & Lacroix's Les Minéraux des Roches.*

‖ In the determination of feldspar microlites it is well to remember the following facts: "Microcline is rarely, or never, seen in the condition of microlites, while the

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Convergent Light: All plagioclases show the emergence of a bisectrix,* more or less oblique, on brachy pinacoid $\infty P\breve{\infty}$ (010) cleavage faces. These cleavage faces show no twin lamellæ, unless twinning after *Pericline* law occurs, in which case the determinations are much more complicated. Optical character, depending on variety, (+) or (—).

Alteration: Partly the same as in orthoclase, forming kaolin, muscovite, etc. Calcite and epidote are more common as side-products, and zeolitization also occurs in some rocks. The basic feldspars appear to decompose more easily than the acid. Decomposition makes the crystals cloudy.

Differentiation:

(*a*) From ORTHOCLASE.—By repeated twinning after *Albite* law, giving between crossed nicols a series of alternate dark and light bands, and by interference colors being a little brighter.

When *Albite* twinning is absent the distinction is very difficult.

(*b*) From MICROCLINE.—By common absence of the microcline *gridiron* structure between crossed nicols.

Specific gravity separations, by use of heavy solutions, and chemical and micro-chemical tests (for the relative amounts of K, Na and Ca) may be used to confirm other determinations in differentiating the members of the feldspar group.†

REMARKS: The plagioclases may have the same two general habits as orthoclase, being glassy and colorless in the younger eruptive rocks, and dull and cloudy in the granular and porphyritic, older, massive rocks. They occur in rocks of intermediate and basic composition.

Albite is found in granite, gneiss (especially with high percentage of silica), diorite, etc., and frequently as a secondary constituent (secondary feldspar‡) in the feldspar-quartz mosaic of mechanically metamorphosed rocks. It may also be present in acid eruptive rocks.

Oligoclase is very frequent in granite, syenite, gneiss, diorite, trachyte, andesite, diabase, etc.; and particularly accompanies orthoclase.

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associations of labradorite and albite are so different that there is little danger of confounding them. Labradorite is the commonest product of the consolidation of the basic eruptives, and albite almost invariably results from metamorphism, frequently from the contact of igneous rocks on the calcareous clastics." N. H. Winchell, Determination of the Feldspars, *Am. Geol.*, Vol. XXI., No. 1, p. 33, 1898.

* For the positions of the optic axes, bisectrices, etc., relative to the cleavage plates of the different plagioclases, see *Iddings' Rosenbusch*, p. 302.

† These tests are only possible on pure and fresh material. The specific gravity increases with the Ca % (albite 2.62, anorthite 2.75).

‡ In clear unstriated granules, which may be distinguished from quartz by biaxial interference figure in convergent light.

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Labradorite is confined more to the gabbros,* basic eruptive rocks and crystalline schists, rich in amphibole and pyroxene.

Anorthite occurs in gabbros, the most basic porphyrites, basalts, etc.

Chemical corrosion and mechanical deformation,† may take place as in orthoclase.

Anorthite and labradorite are more or less decomposed by hydrochloric acid, while albite and oligoclase are not acted on by the acid.

The Ca, Na feldspar (anorthite end of series) of the gabbros may alter, under the effect of dynamic action, into *Saussurite*. This is an opaque, white substance, consisting of a confused aggregated mass of granules and fibres of several minerals, chiefly zoisite, epidote and secondary feldspar (albite).

Anorthoclase (Na, K, feldspar).—Recognized between crossed nicols by intersecting systems of extremely fine, indistinct twin lamellæ. On basal sections the twin lamination may only appear when sections are very thin. The triclinic character is obscure. Anorthoclase can be best distinguished from orthoclase in sections at right angles to base 0 P(001) and brachy pinacoid $\infty P\breve{\infty}$ (010). In these sections highly twinned areas pass into others free from twinning, without any visible boundary between them.

It occurs in augite-syenite and "Rhombenporphyr" of Norway, acid augite-andesite of Pantelleria and in the porphyries of the Hartz.

CYANITE, Disthene.

ANISOTROPIC. BIAXIAL. TRICLINIC.

COMPOSTION: $(AlO)_2 SiO_3$. ELONGATION $\| c'$.

Usual Appearance in Sections: Prisms and parallel columnar aggregates. Crystals blade-like and elongated parallel to prism axis; cross-sections showing two long parallel edges, and four shorter edges. Twinning very frequent. Colorless, but may be bluish and spotted. *Relief* high and surface rough ($n' = 1872$). Cleavage perfect, parallel to macro pinacoid $\infty P\infty$ (100), appearing as sharp cracks, parallel to longest edges in cross-sections; less distinct, parallel to brachy pinacoid $\infty P\breve{\infty}$ (010). Parting parallel to base 0 P (001). Carbonaceous matter may be included at times. Pleochroism (colorless to blue $\| c'$) not noticed except in colored crystals.

Crossed Nicols: Double refraction quite strong ($\gamma - a = 0.016$). Interference colors upper 1st order, yellow, red, violet, etc. *Extinction* angles observed in all sections (being triclinic), reaching a maximum of 30° on macro pinacoid $\infty P\bar{\infty}$ (100). Extinction on base, about parallel to most perfect cleavage. In *convergent light* axial angle large; optical character (—).

Alteration: Seldom observed.

REMARKS: Found in mica-schists, granulites, metamorphic schists, eclogites, etc., commonly associated with garnet. It is not attacked by acids. H., 5 to 7. Sp. gr., 3.6.

* The tendency of labradorite in gabbros to twinning, after both *Albite* and *Pericline* laws, is to be noted.

† Werveke's (N. J. B., 1883, II, 97) theory is that a twin lamination may be caused by the forces producing mechanical deformations, as movement in the magma and mountain making pressure. Such lamellæ are characterized by the fact that their extent and course seem to depend on fracture lines in the crystal.

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SERPENTINE.

AGGREGATE.

ELONGATION (of fibres) ‖ $\mathfrak{c}'$.

COMPOSITION: $H_4Mg_3Si_2O_9$, with replacement by Fe.

Usual Appearance in Sections: Fibrous or scaly in structure.

Color.—Colorless, yellowish or greenish. May be colored a deep reddish-brown by limonite.

Index of Refraction.—$n' = 1.54$ (about the same as balsam).

Relief.—None and surface smooth.

Polarized Light:

Pleochroism.—Very feeble.

Crossed Nicols:

Double Refraction.—Rather weak ($\gamma - \alpha = 0.009$ to 0.011).

Interference Colors.—Middle 1st order, gray, white, yellow, etc. The aggregate structure is distinctly seen between crossed nicols. Fine, confusedly fibrous, aggregates may appear isotropic.

Differentiation: From CHLORITE.—By more usual weaker pleochroism, but this distinction may be very difficult.

REMARKS: Serpentine is essentially a decomposition product,* principally from chrysolite and (non-aluminous) amphiboles, pyroxenes, etc., Fig. 21. Pieces of the undecomposed parent mineral are often present, giving to the section a mesh-like or net-like appearance. A knowledge of the composition of the parent mineral may aid in distinguishing serpentine from chlorite, which is a decomposition product of aluminous minerals.

Serpentine is found in ophiolites, and the altered basic igneous rocks, pyroxenites, peridotites, etc. It may also form a rock by itself. Serpentine is attacked quite strongly by hydrochloric acid, still more so by sulphuric acid. H., 2.5 to 4. Sp. gr., 2.5 to 2.7.

KAOLINITE, Clay.

COMPOSITION: $H_4Al_2Si_2O_9$. EARTHY AGGREGATE.

Usual Appearance in Sections: Loose, earthy aggregates, formed by weathering of feldspars, elæolite, scapolite and other silicates. Aggregates of kaolinite are cloudy and scarcely translucent, and no perceptible change takes place between crossed nicols. Separate scales are transparent and colorless, and may show pseudo-hexagonal forms. There is no *relief* to the scales ($n' = 1.54$), and the double refraction is strong like muscovite.

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* Rosenbusch considers the fibrous serpentine to result from the decomposition of chrysolite and amphibole, and the scaly serpentine from the pyroxenes.

Weinschenk has maintained that serpentine may have been an original product of igneous fusion.

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Differentiation: From colorless MICA. When in scales is only distinguished by proving absence of alkalies chemically.

REMARKS: Kaolinite is insoluble in hydrochloric and nitric acids, but decomposed by sulphuric acid. H., 2 to 2.5. Sp. gr , 2.2 to 2.65. The mechanical separation from muscovite by sp. gr. cannot be used on account of the scaly character of the two minerals.

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CHAPTER V.

Methods of Preparing Sections.

The methods described will be those used in making rock sections. The general principles involved are the same for both rock and crystal sections; although more difficulties are encountered in making the latter, due to the sections being required in some

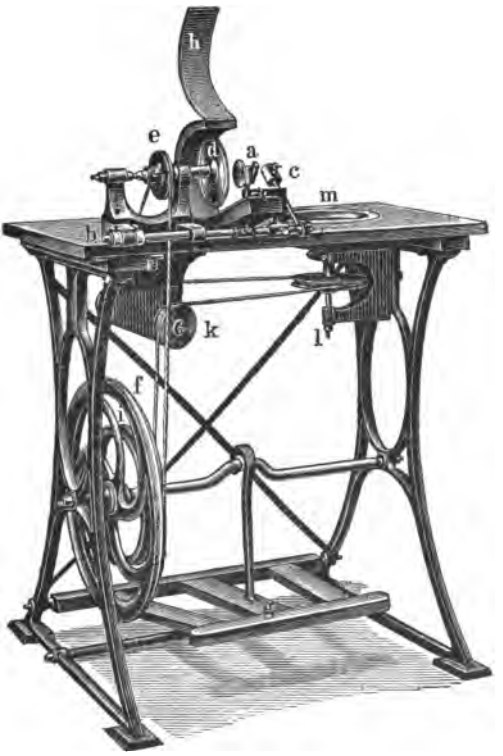

Fig. 38.

definite direction or of some precise thickness, or on account of the soft or fragile character of the crystals.

In the case of rock sections any section, taken "at will" through the rock, will generally do.

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Cutting and Grinding Machines.

Many different kinds are used, the power being furnished by steam, electric motor,* or by the hand or foot. A convenient type of combined cutting and grinding machine† is shown in Fig. 38.

The chip or fragment of rock to be sliced by this machine must be comparatively small in size and first have a smooth surface ground upon it by emery on the rotating plate or lap *m*. The

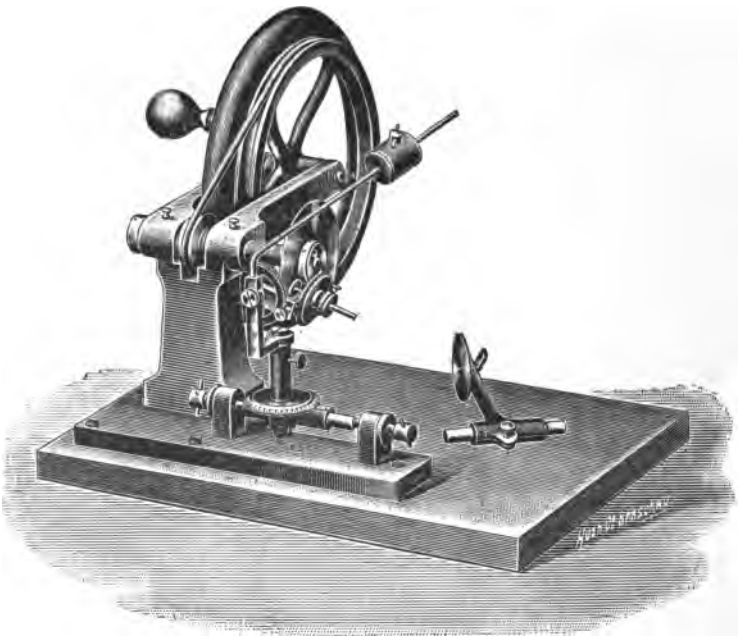

FIG. 39.

fragment is then cemented to the plate *a*, the holder of which can be so adjusted on the rod *b* that a slice of any required thickness can be cut by the saw *d*. The saw must revolve from above downward, as otherwise it would unscrew itself; and during the cutting a steady, light pressure against the saw can be maintained by the counterpoise *c*. The moistened emery is kept in the basin *h* and

* A Crocker-Wheeler motor of ¼ H. P. will be large enough for an ordinary laboratory machine.

† Made by Voigt and Hochgesang, Göttingen. Price, $70.00.

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fed to the saw by a spoon or some other device. Diamond saws are only needed in the case of hard rocks.

For cutting sections of crystals in definite directions a form of small hand apparatus* is shown in Fig. 39.

This cut shows how the plate, to which the crystal is cemented, can be given definite rotation in two directions. The simpler crystal holder, appearing loose on the stand, may be used when a section is required parallel to the face of the crystal cemented to the holder.

In these machines the cutting is done with rotating saws of sheet-tin, usually charged with either diamond dust or emery.

In the case of a very small crystal a section, parallel to any desired face, can be obtained by cementing this face to a suitable frame or holder and grinding down by hand on a glass plate with emery, the final polishing being given with rouge. When the section required is not parallel to a crystallographic face or cleavage it must be verified geometrically with reference to other faces. If the crystals are soluble in water, some other liquid, as α bromnapthalin or benzine must be used in grinding; and very fragile crystals are rubbed down on a ground glass plate without emery or rouge, simply using bromnaphthalin or some other appropriate liquid.

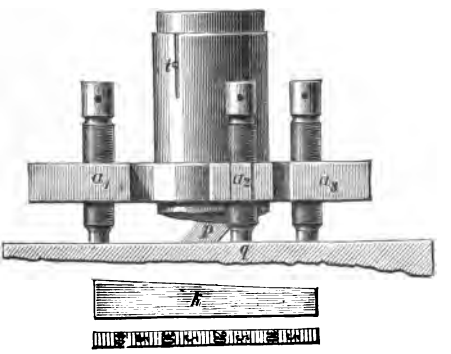

FIG. 40.

When sections of a crystal are desired with strictly parallel faces, the form of grinding apparatus shown in Fig. 40 can be used.

This apparatus consists of a cylinder, held within a suitable frame supported on three set-screws a_1, a_2 and a_3 of hard steel.

* Made by Voigt and Hochgesang, Göttingen. Price, $15.00.

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The lower surface of the frame and consequently the bottom of the cylinder can be adjusted by the wedge *k* and the set-screws so that it is exactly parallel to the grinding surface of the glass plate. The crystal to be ground down, *p*, is cemented to the bottom of the cylinder, and the whole apparatus rubbed over the grinding surface of the plate. The pressure of the hand on the upper part of the cylinder regulates the pressure of the crystal on the grinding surface. In this way a surface is obtained which is exactly parallel to the surface cemented to the cylinder.

Sections of definite thickness can also be obtained by using this apparatus; for the adjustments with the wedge *k* may be so arranged that, when the stop *t* in the cylinder has reached the bottom of the slot in the frame, the lower surface of the cylinder will be the required distance from the grinding surface of the glass plate. The wedge is graduated so that the value of one division on the sloping top is known in *m m.* of vertical distance.

Saws.

Saws,* of about six inches in diameter made from $\frac{1}{36}$ inch sheet-tin, are convenient for general work, and may be charged with diamond dust by the operator as follows:† Crush one or two carats of rough crystals of diamond-bort in a small steel mortar to about the condition of fine sand, care being taken not to reduce the diamond to powder. Transfer the dust to a piece of flat iron and, after collecting it in a heap, moisten with a drop of oil. The cutting edge of the tin disk must now be prepared by making a series of incisions ($\frac{1}{16}$ inch deep) on the outer margin. This can be done by striking the disk with a sharp, thin knife edge. The larger the number of incisions and the closer they are together the better. Charging the saw is accomplished by gently hammering the edge against the iron plate, upon which is the paste of diamond dust and oil. The disk must be slowly rotated during this charging process, which should be continued until all portions of the edge have been gone over two or three times.

Instead of charging with diamond dust the saws may be used with emery. The edges of the saws should first be "upset," as

* Circular tin saws, 6 and 8 inches in diameter with ¾ to 1 inch centre apertures, charged with diamond dust can be obtained from Wm. Kerr, 543 Westminster St., Providence, R. I.

† *School of Mines Quarterly*, Vol. XI., p. 32.

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just described, and then while rotating charged with emery. The emery in the state of mud can be applied with the thumb and fingers, or the saw can be allowed to pass through a tray of emery mud. The finer grades of emery (nos. 100 to 120) should be used.

The method of mounting saws, of course, depends on the way the saws and spindles are constructed. It is well, however, to have the hole in the center of the saw-disk sufficiently large to allow of adjustment for accurate centering.

Cutting.

During the process of cutting a lubricant must be used on the saw. Petroleum has been recommended by some, but water seems to be the most used. Holding a piece of soap against the cutting edge will also reduce friction. It is very convenient to carry the water to the saw through a very small lead pipe, which permits of easy adjustment, so that the water can be delivered at just the right spot, the flow of water, of course, being regulated by a stop-cock.

Another method for cutting sections is used by the U. S. Geological Survey at Washington, D. C. The apparatus consists of an endless wire of soft iron, about $\frac{3}{32}$ inches in diameter, revolving over two pulleys or wheels, one of which is driven by steam-power. The wire is charged by dipping the fingers in water; taking up a little fine (120 grade) emery and holding the fingers against the wire above the section. The wire revolves so as to cut downwards, thus carrying with it the emery taken from the fingers.

In cutting sections the thickness, of course, depends on the character of the rock; the more porous and fragile the rock the thicker the section should be made, an ordinary section being about as thick as a silver quarter of a dollar.

Very often by skill and practice a suitably shaped chip or fragment can be detached from the specimen with a hammer or with a hammer and cleavage chisels; thus avoiding the delay and trouble involved in the use of the section cutter.

Grinding Plates or Laps.

Copper laps, about 7–8 inches in diameter and ½ inch thick, seem to be best for general purposes; although laps made of lead

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or cast iron are also used. A lead lap, being soft, holds the emery well and thus hastens the grinding away of the section; but at the same time its own smooth surface is soon destroyed. A cast iron lap is much harder and retains its smooth surface better, but does not hold the emery so well and therefore retards the process of grinding. Copper, being intermediate in hardness between lead and iron, seems to combine the advantages of both.

It is always good practice to have at least two laps, one for the preliminary grinding with coarse emery and the other for the final grinding with the finest grades of emery. In this way one lap is always kept with a smooth surface, making it possible to give a uniform, plane finish to the section.

The surface of the laps should not be exactly plane, but turned or finished so as to be a little higher ($\frac{1}{32}$ of an inch for diameter of 8 inches) at the axis than at the periphery; the idea being to compensate for the more rapid abrasive action towards the periphery.

Cementing.

For grinding down to a proper thinness for transparency it is necessary to *cement* the fragment of rock to a holder, which consists of a small piece of plate-glass about $\frac{1}{8}$ inch thick. If the piece of rock has been cut by a good diamond saw the surface will be comparatively smooth and uniform, and may only need polishing (described under *grinding*) before cementing. When, however, the piece of rock is in the shape of a chip or rough fragment it is first necessary to prepare a smooth ground surface on one side (described under *grindiug*) before it can be cemented to the glass holder.

The pieces of plate-glass used should be free from flaws, bubbles or anything tending to destroy uniformity of surface, and should be a little larger than the chips or slices of rock for which they are to act as holders. Hardened Canada balsam, or, better yet, a cement made of a mixture of shellac and Venice turpentine,* should be used.

* "Half a pound or less of ordinary shellac is melted in a flat bottomed open vessel over a Bunsen burner. Then an equal quantity of Venice turpentine is carefully added under constant stirring. The mass should be allowed to boil for about ten minutes, during which the stirring is continued. Then small quantities are poured in separate heaps on an iron plate or other cold surface and rolled into sticks about seven inches long and half an inch thick."

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The process of cementing is carried on as follows: Heat the glass support over an alcohol lamp or a Bunsen burner, place it on a good non-conductor of heat, as a piece of wood, and rub it with a stick of the cement until a sufficient quantity has been melted off. The piece of rock should then be treated in the same manner, applying the cement to the smooth finished portion. Care must be taken that neither the glass nor rock preparation are heated too much, as this would cause the cement to smoke or bubble. After placing the rock preparation and plate together, use quite a little pressure in order to drive out all superfluous cement. Examine now, through the glass, the contact surface and see that it is entirely free from bubbles, etc.

Bubbles are usually caused by overheating of the parts before cementing. If only very few bubbles are seen, they may generally be removed by moving the rock preparation rapidly back and forth over the glass plate. If the bubbles are numerous or cannot be removed in the manner just described, the rock preparation must be separated from the glass plate and the cementing done over again.

Bubbles must *not* be allowed to remain, as the portions of the rock over them, not having any cement backing, are ground away leaving holes in the section.

Grinding.

After the rock preparation has been cemented to its glass holder it is ready for the grinding process. The copper lap for the first grinding, is put in place, and, after it has commenced to rotate, is charged with emery and water. This can conveniently be done by dropping on the emery and water, either with the fingers or with a small bunch of rags at the end of a stick. A large camel's hair brush may be used for putting on the finest emery. The emery is distributed over the rotating lap by the motion of the rock preparation during grinding. The kind of emery used for this first grinding depends somewhat on the character of the rock section. If the section is composed of a hard, compact, fine-grained rock, the first emery used may be quite coarse; the coarser the emery the more rapid being the grinding down. For rough, quick work, Nos. 80 to 100 emery can be used until the section becomes quite thin; then, still using the same lap, substitute the finest corn emery (next coarsest to flour emery) and continue grinding until

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the section becomes quite translucent. The lap must now be changed, and the grinding finished with the finest emery dust.

Too great care cannot be given to cleanliness while doing this sort of work. A single grain of coarse emery, getting on the lap or section during the final grinding, will often spoil the whole work by making a bad scratch. In grinding down the section, great care must be taken to see that the grinding surface is kept parallel to the surface cemented to the glass. The section is firmly pressed against the lap by means of two or three fingers, depending on its size, and uniform pressure should be maintained over all parts.

The section should be examined frequently, and if it is noticed that one part is thicker than another, place the section on the lap so that the thicker part is towards the periphery, and put a little more pressure upon this part. Gutting or grooving the copper lap is prevented by moving the section from center to periphery and back, at the same time giving to it a slight rotary motion. It is best to have the lap revolve from right to left (in the opposite way from the hands of a watch), as, holding the section on the right side of the lap, it is easier to keep it in place by a pulling motion rather than by pushing it against the motion of the lap. In the final stages of grinding and polishing great precaution must be exercised, as one or two turns too many of the lap will often tear away a large part of the very thin section. The section should be frequently examined, by transmitted light, with a small, low-power microscope, a drop of water or oil being put on the section to render it more transparent. If the section is thick and fastened to the plate-glass with a good deal of cement, it will be found convenient, after the section has been ground quite thin, to remove most of this cement from around its edges. If this is not done, it may delay the final work of grinding down. A good rock section should be made so thin that all the transparent and translucent component minerals can be examined and studied. In France well made rock sections average 0.02 *mm.* in thickness, while elsewhere they vary from 0.03 to 0.05 *mm.* The last part of the final grinding and polishing can be done by the hand on a ground-glass plate, using the finest emery dust or rouge and water.

Flour emery may also be used entirely for grinding, and the finest emery dust for polishing. The finer emery makes better work, although it takes more time, and is much safer for porous or

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brittle sections, as the danger of tearing away pieces of the section is avoided. In the case of a porous or decomposed rock it is well, before grinding, to boil the section in Canada balsam or other equivalent material, so as to fill all the pores and interstices, thus making the section more compact and less liable to chip away. Sometimes it may even be best, before grinding, to mount the section on its permanent glass slide, so that when it has been ground thin enough, the cover can be put on without running any risk in transferring the section. The only objection is that the glass slide may be a little scratched by the emery.

Mounting.

When the section is thin enough and of uniform surface it is ready to be transferred and mounted upon its permanent glass slide. The glass plate, which has held the section during the grinding, is gently heated, and, as soon as the cement begins to soften, the section is very gently pushed off into a shallow cup or evaporating dish containing turpentine or alcohol. Turpentine is convenient for general use, because common alcohol (on account of the water it contains) unites with the shellac to form a kind of white pasty substance, which is sometimes hard to remove from the section. The section should be carefully cleaned in the turpentine or alcohol bath by means of fine camel's hair brushes. A section-lifter, made from a piece of broad, flat watch-spring fastened to a small handle, is then gently placed under the section, which is lifted out of the bath in an inclined position so as to allow the liquid to drain off. If a drop still adheres it can be removed by touching it gently with the finger.

The section is now placed in a tray, upon a piece of white, unglazed paper, so that it may thoroughly dry; after which process it is transferred to a glass slide, and, if necessary, its rough edges chipped off with a knife.

If the section is very large, and it is desired to mount it in two pieces, it can easily be divided by holding one half tightly between two glass slides and gently bending the other half with the fingers. The fracture will take place along the edges of the glass slides.

A mixture of gum damar and benzole is recommended for mounting, the claim being made that gum damar does not turn yellow with age, whereas Canada balsam may do so. Two solutions

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of gum damar and benzole are used. One very thin, about the consistency of water, the other quite thick, about the consistency of mucilage. Both solutions are prepared by dissolving the gum damar in benzole and filtering through a linen or silk rag. If the solution is too thin it can be thickened by placing the bottle in a warm place and allowing the excess of benzole to evaporate, or if too thick, more benzole can be added. It is convenient to keep the solutions in short glass bottles, with wide necks and glass covers instead of corks. The solutions can be applied with glass rods.

When the section is all ready for its final mounting it is carefully centered with a course needle on the glass slide,* and a drop of the thin solution placed at the edge of the section. Capillary attraction will cause it to flow over the glass slide under the section, and while it is soft the section can be again adjusted in place. The slide is then placed in a cool, dust proof place and allowed to stand for about twelve hours, when the cement will be set and the section held firmly in place. The upper surface of the section is then washed with a drop of benzine, and as much as may be necessary of the thick mounting solution placed upon it with a glass rod. A cover of glass of the right size is gently heated and placed in position over the section. Care must be taken not to have the cover too hot, as it would cause bubbles to form in the cement. It is also best to rest one edge of the cover on the cement first, and then lower it gently so as to prevent air bubbles from being included. The cover is adjusted and then held firmly in position by means of a mounting clamp, which presses out all superfluous cement. If a few small bubbles remain near the edges they may be let alone, as they will generally work out by themselves in time. Sometimes a large bubble can be worked out by local pressure with the finger and gentle heating with a small iron rod. If the mounting is unsatisfactory the cover should be removed by heating, the old cement washed off with a camel's-hair brush and benzole, and a fresh cover put on. After the cement has set, the clamp may be removed, but the slide should be left for 24 hours, or longer if necessary, until the cement is quite hard. This takes longer in hot than in cold weather.

* Square glass slides are recommended instead of the oblong slides (1 x 3 inches), which are very apt to project beyond the edges of the stage and be struck by the fingers while rotating the stage.

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The advantage of using two solutions for mounting is that the section is firmly held in place on the glass slide while the cover is being placed over it; there is thus no slipping or sliding of the section, and when the cover is adjusted in place the work is well finished and the section still in the centre of the slide.

Canada balsam, or balsam fir, is also often used for mounting.

Cleaning and Finishing.

When the cement has set the superfluous part is singed by means of a small hot iron rod. Care must be taken not to use too large a rod or to have it too hot, as the cement under the cover might then soften and allow the cover to slip or air bubbles to form. The singeing drives off the more volatile part of the cement, leaving only a brittle residue, which can be easily scraped off with a knife. In some cases it may be necessary to singe and scrape twice. The final cleaning is done with a soft rag and benzole. The slides are now ready to be marked, either with a diamond pencil or with pasted labels.

Convenient Apparatus for Work in a Petrographical Laboratory:

Section lifters made of watch springs, three sizes.
Section holders or clamps for pressing out superfluous cement.
Needle points mounted in light handles.
Easy spring forceps.
Mounting frame for centering section on glass slide.
Small iron rod for singeing.
Small camel's hair brushes.
Cutting pliers and forceps.
Set of wooden section trays.
Glass stopper bottles for benzole, benzine, turpentine and alcohol.
Open neck bottles, with covers for the two mounting liquids.
Rotating mounting stand.
Small microscope for testing transparency of section.
Glass rods.
Small squares and rectangles of plate-glass.
Round, oval and square cover glasses.
Glass slides with ground edges.

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CHAPTER VI.

Chemical and Mechanical Tests.

These tests may be necessary to confirm an optical determination or to assist in the differentiation of the closely related species of a group, as, for example, the different plagioclases in the feldspar group. They may also be useful in the case of opaque substances.

The ordinary chemical methods employed in mineral analyses are often not applicable, on account of the minute size of the mineral under investigation and the lack of sharpness in the reactions. Those methods* are to be preferred which produce crystallizations independent of the relative proportions of the materials taking part in the reaction and also of the physical conditions involved.

The tests can be made either on the crystal in a rock section or on the isolated crystal or fragment, the latter method being preferable when possible.

Chemical Tests Made on Crystal in Section.

The part of the section to be tested must be prepared by thorough washing with alcohol and benzole to remove all traces of balsam. If the section is covered, the cover glass can be cut across with a diamond, and, after heating, the desired portion removed with a knife edge. Any portion of a section can be isolated by surrounding it with a rim of viscous balsam or by putting on a new cover-glass, in which a small hole has been made.† This hole can be accurately adjusted over the special portion of the section and the balsam removed by alcohol and benzole.

The treatment of rock sections with ordinary acids, such as hydrochloric, may show the presence of easily soluble min-

* Reference can be made to the publications on this subject by: Fouqué, Borichy, Behrens, Haushofer, Streng, Klément and Rénard.

† In case an acid is to be used which would attack glass, the cover-glass can be replaced by a thin perforated disk of platinum.

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erals * and carbonates, or distinguish silicates that are soluble with jelly, or produce etched figures on the minerals.

Test for Carbonates. When only present in very minute grains the test can be made as follows: Cover the rock section with a drop of water and a cover-glass, then allow a drop of acid to slowly diffuse through the water film. The glass cover will prevent the escape of the gas bubbles† which will thus surely be detected.

If necessary the section can be warmed by heating the projecting part of a suitable stand, placed under the section on the stage of the microscope.

Test for Gelatinizing Silica. Cover the carefully cleansed section with a little dilute acid (commonly hydrochloric) and let stand. If too much acid is used the resulting gelatin will spread over the whole section and not appear simply on the gelatinizing silicate. Warm the section, if necessary, and finally rinse off the remaining acid thoroughly with water. Do not allow the action of the acid to continue too long, as it is desirable to obtain only a very thin film of gelatinous silica over the minerals attacked, so that the optical tests can still be made on these minerals. If after the first trial the action has not been pronounced enough, the test should be repeated.

The transparent film of gelatinous silica is made more visible by covering the section with a drop of water, containing a dilute solution of fuchsine. After standing for some time the section should be washed, when only those portions covered by the gelatinous film will show the color stain.

Etched Figures.‡

The results of etching tests can not be regarded as very satisfactoty in the case of sections of minerals in rock sections, on account of doubt as to the crystallographic orientation of these sections.

The symmetry of the etched figures depends essentially on the

* The bases in solution can be determined by different methods of analysis, for which the student is referred to more elaborate works on this subject. In some cases it may be very advantageous to treat the section with acid, to remove certain soluble constituents, when other minerals not distinctly seen at first may be made more apparent.

† The gas may be H_2S from a soluble sulphide, in which case the solution containing the bubbles will color filter paper moistened with lead water.

‡ *Geol. and Nat. Hist. Survey of Minn.*, XIX., Ann. Rept., p. 42; also A. J. Moses, *Characters of Crystals*, Chap. XVI.

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relation of the crystal faces on which they are obtained to the planes of symmetry.

The forms of the etched figures differ on the same face of a mineral, depending on the reagent used, but their degree of symmetry is independent of the reagent or its degree of concentration. The sharpest figures are produced on crystal and cleavage faces, the figures being less perfect on artificially prepared faces, even when polished.

The etching tests may, however, be tried to prove the presence of twinning, or to distinguish between minerals of similar appearance but belonging to different systems.*

Various acids or alkalies are used to produce the etched figures, depending on the mineral to be tested. Different factors influence the formation of good etched figures, and that method must be used which seems to give the most satisfactory results in the given case. The action of the reagent should be sufficiently pronounced to develop clearly the etched figures; at the same time the tests must be stopped before the solvent action has been too powerful.† After treatment for etching the section should be thoroughly washed and examined in some fluid of weak refraction (with n lower than that of the crystal section), such as water or air.‡ The objective, of course, must be focused on the surface of the section.

Heating Sections to Redness.§

The part of the section to be tested must be removed from the object-glass, carefully cleansed of balsam, and held on platinum foil in the oxidyzing blowpipe flame. After the test the fragment used may be remounted in Canada balsam for study.

As a result of heating:

Colorless, hydrous minerals (zeolites and chlorites) become cloudy in appearance.

Colorless silicates, containing protoxide of iron (as olivine, or

* The symmetry of the etched figures would, of course, be related to the system of crystallization.

†A. J. Moses, *Characters of Crystals*, Chap. XVI.

‡ When it is desired to preserve the section and at the same time to study the surface, covered with a film of air, the edges alone of the cover-glass should be cemented.

§ *Geol. and Nat. Hist. Survey of Minn.*, XIX., Ann. Rept., p. 50.

Thin sections of 2–3 sq. mm. area are of a convenient size, and they should be subjected to a red heat for 1½–3 minutes. Too long a continuance of heat may render the sections too dark or lessen their transparency or produce melting.

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faintly colored pyroxene or amphibole), become red or reddish-brown.

Colored minerals may change their color, chloritic substances becoming brown or black if heated enough.

Hornblende always becomes pleochroic, and olivine sometimes becomes so.

Members of the sodalite group may be turned blue, if not already of that color.

The dichroism (yellow to blue) of almost colorless iolite may be developed.

Carbonaceous particles may be distinguished from the iron oxides by being consumed.*

METHODS OF ISOLATING CRYSTALS OR MINERAL FRAGMENTS FOR TESTING.†

For the application of these methods the rock or aggregate of minerals should be reduced to homogeneous ‡ grains of uniform size (preferably crystals or cleavages) and not to powder. This is best done by pounding in a metal mortar, avoiding all grinding motion.

The separations required may be made by specific gravity solutions or magnetic methods, alone or combined; and in some cases may be assisted by chemical action.

The *hardness* of the homogeneous grains may be obtained by pressing them firmly into the end of a lead stamp or holder and trying the effect of scratching upon the faces of minerals of known hardness.

When other methods fail it may be necessary to separate single grains from a mixture by hand. A grooved piece of plate-glass, passed beneath the objective of the microscope, will be found useful. The desired grains in this groove can be picked out by means of a piece of fine waxed thread or a fine pointed stick moistened at the end.

* This test may vary, in many cases graphite not being consumed even after long heating.

† The isolation of material for investigation is of more interest for the lithologist or chemist than for the student of optical mineralogy; therefore only a very brief outline of some of the methods employed will be given.

‡ The grains passing through different meshes are investigated microscopically to ascertain which size grains are homogeneous; the rest of the sample should then be reduced to grains of this size.

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*Specific Gravity Separation.** Accomplished by use of fluids of different specific gravity. These fluids can be made specifically lighter by dilution, and hence the fragments will fall to the bottom in order of decreasing density. Dilution of the heavy solutions to any specific gravity may be affected empirically until the solution will just suspend a fragment of a mineral having the desired specific gravity; or the exact specific gravity of the solution may be determined by the Westphal balance.

List of *indicators* that may be used to determine the limits of the specific gravity of the solution to be used for separation purposes (V. Goldschmidt).

No	Name.	Locality.	Sp. Gr.	No.	Name.	Locality.	Sp Gr
1.	Sulphur,	Girgenti,	2.070	11.	Quartz,	Middleville,	2.650
2.	Hyalite,	Waltsch,	2.160	12.	Labradorite,	Labrador,	2.689
3.	Opal,	Scheiba,	2.212	13.	Calcite,	Rabenstein,	2.715
4.	Natrolite,	Brevig,	2.246	14.	Dolomite,	Muhrwinkel,	2.733
5.	Pitchstone,	Meissen,	2.284	15.	Dolomite,	Rauris,	2.868
6.	Obsidian,	Lipari,	2.362	16.	Prehnite,	Kilpatrick,	2.916
7.	Pearlite,	Hungary,	2.397	17.	Aragonite,	Bilin,	2.933
8.	Leucite,	Vesuvius,	2.465	18.	Actinolite,	Zillerthal,	3.020
9.	Adularia,	St. Gotthard,	2 570	19.	Andalusite,	Bodenmais,	3.125
10.	Elæolite,	Brevig,	2.617	20.	Apatite,	Ehrenfriedersdorf,	3.180

A method of dilution, to any desired specific gravity, by addition of a measured quantity of the diluent may be employed by using the equation †

$$v_1 = \frac{v(D - \Delta)}{\Delta - 1}$$

where v equals volume of the solution, D its specific gravity, v_1 the volume of the diluent,‡ and Δ the density desired.

Among the heavy solutions employed may be mentioned:

Thoulet's solution of potassium-mercuric iodide ($KI : HgI_2 = 1 : 1.24$), maximum specific gravity 3.196. Klein's solution of cadmium borotungstate ($2H_2O$, $2CdO$, B_2O_3, $9WoO_3 + 16H_2O$), maximum specific gravity 3.6. These two solutions can be mixed

* Further reference can be made to *Iddings' Rosenbusch*, p. 99. A convenient form of apparatus is also described in *School of Mines Quarterly*, Vol. X., p. 284, 1889.

† *Dana's Text Book of Mineralogy*, p. 175, 14th. ed.

‡ The diluent is usually distilled water. In some cases this method is not so reliable as the empirical method, especially in the case of Thoulet's solution due to the contraction which takes place.

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with water in any proportion without being decomposed. Solution of barium mercuric iodide, maximum specific gravity 3.588, cannot be diluted with water. Methylene iodide (CH_2I_2), specific gravity 3.3243 at 16°C. varying with the temperature, can be diluted with benzole but not with water.

Nitrates of silver and thallium * ($AgNO_3$: $TlNO_3 = 1:1$) fuse at about 75°C. to a clear mobile liquid with specific gravity over 4.5. Can be mixed while melted with water in all proportions; but cannot be used for separation of sulphides, as they are attacked by it.

Possible chemical action between the minerals and heavy solutions must not be overlooked in this method of separation.

The funnel-shaped apparatus for these separations must be so arranged, with stop-cocks, etc., that the heavier material collected at the bottom can be easily drawn off or removed at any stage of dilution.

These separations, for various reasons, are not always complete, but the best results are obtained when the processes are repeated several times.

Electro-magnetic Separation. All iron-bearing minerals may be separated from those free from iron by an electro-magnet.

The factors influencing the attraction of a mineral by an electro-magnet are not definitely known, and do not seem to depend on the percentage of iron, as chromite (rich in iron) is not attracted while other minerals with small percentages of iron are attracted.

Minerals, such as amphibole, pyroxene, epidote, olivine and garnet (containing iron), may often be separated by an electro-magnet by regulating its magnetic moment.

Separation by Chemical Means. Very many different methods may be used, depending on the nature of the work to be accomplished; but they are generally only reliable in the hands of a good chemist. The material should be in the state of fine powder.

As an example may be mentioned the treatment with pure concentrated HFl, by which the minerals of a rock are attacked in a certain sequence, the feldspars and related minerals first, then the quartz and finally the ferro-magnesium silicates, such as amphibole, pyroxene, olivine, etc.

* S. L. Penfield, *Am. Jour. Sci.*, Vol. L., p. 446, 1895. In this article a convenient form of separating apparatus is also described.

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Micro-Chemical Reactions.

The first requisite is to bring the substance to be investigated into solution. This can be done in the case of non-silicates by the ordinary solvents, while silicates can be decomposed and investigated either by the methods of Borichy or Behrens. Both methods rest upon the recognition of the forms, etc., of artificially produced crystals.

The size of a fragment for testing may vary, according to circumstances, from that of a popy seed to a pin head. Good results are recorded from fragments of not more than 0.2–0.7 sq. mm.

The substance to be tested is placed on glass, protected by a film of balsam, and covered with a spherical drop of the solvent,* which should be allowed to act until all the different elements composing the sample are in solution (in the case of a very small fragment until it has all dissolved). Transfer the solution to another protected object-glass, and, after evaporation, the crystallizations characteristic of the different elements will be seen.

If the evaporation is too rapid and the crystallizations incomplete, the residue should be redissolved in water, or a very dilute solution of the solvent employed, transferred to a fresh glass and allowed to recrystallize.

Borichy's Method.† (Hydrofluosilicic Acid.)

This method has the advantage of simplicity of manipulation and relative distinctness in results; but on the other hand these results are only obtained after several hours, and the temperature has an influence on the crystalline forms obtained. It is well to make the tests in a temperature of about 15° C.

Put a spherical drop of pure hydrofluosilicic acid ‡ on the fragment and leave it for some hours in damp air until the action has

* For micro-chemical work the reagents should be applied in very small drops, which spread out on glass to discs 2 mm. in diameter. For manipulating the reagents use platinum wires, 0.5 mm. in thickness.

† "*Elemente einer neuen chemisch-mikroskopischen mineral-und Gesteins-analyse.*" Prag, 1877.

Translation of above by Winchell in *Geol. and Nat. Hist. Survey of Minn.*, Vol. XIX., Ann. Report, 1890.

‡ The strength of the solution should be about 3½ %; for if too weak many minerals do not give satisfactory results, and if too strong a very large number of fluosilicate crystals are formed together with the separation of much silica, thus making it impossible to carefully differentiate the crystals with a microscope.

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been sufficient, then transfer it to a dry air bell-glass and allow evaporation and crystallization to take place.

For the microscopic examination the objective (200–300 diams. best for these observations) can be protected with glycerine and a mica disc or thin cover glass, or the drop can be all evaporated and the crystals covered with liquid balsam and a cover-glass.

Crystallizations Obtained by Borichy's Method.

Potassium. From hydrofluosilicic solutions,* isotropic, colorless crystals of K_2SiFl_6, in cubes, octahedra or combinations of these forms with the rhombic dodecahedron. Apparently orthorhombic crystals may form from acid solutions and at a low temperature, but if these crystals are dissolved in hot water and recrystallized they will assume the normal forms.

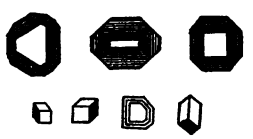

FIG. 41.—Fluosilicate of potassium.†

Platinic chloride will produce under proper conditions sharp, yellow octahedra of K_2PtCl_6.

Sodium. From hydrofluosilicic solutions, colorless, very weakly doubly refracting, hexagonal crystals of Na_2SiFl_6, which are generally longer the higher the percentage of calcium in the solution. This test is very certain even for small amounts.

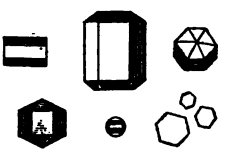

FIG. 42.—Fluosilicate of sodium.†

Calcium. From hydrofluosilicic solutions, monoclinic crystals of $CaSiFl_6 + 2H_2O$ of various forms, generally spindle-shaped, with not very strong double refraction. The crystals have seldom straight-edged boundaries and are often grouped in rosettes. The addition of dilute H_2SO_4 decomposes the crystals, recrystallization yielding long prismatic crystals of gypsum (distinction from strontium).

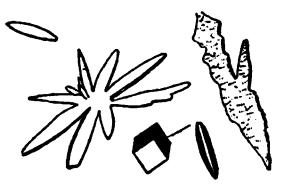

FIG. 43. — Fluosilicate of calcium.†

Treatment with HFl and dilute H_2SO_4 (in excess), producing on evaporation characteristic crystals of gypsum, furnishes a very delicate test for small percentages of calcium.

* As most of the rock-forming minerals that would be investigated are silicates, the hydrofluosilicic solutions can also be obtained by treatment with HFl.

† After Lévy and Lacroix.

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Magnesium. From hydrofluosilicic solutions, rhombohedral crystals of $MgSiFl_6 + 6H_2O$ with plane faces and sharp edges. The crystals are colorless and strongly doubly refracting with positive optical character.

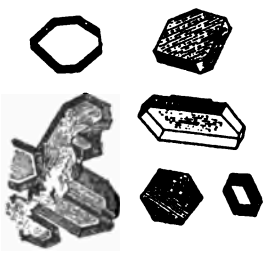

FIG. 44.—Fluosilicate of magnesium.*

The formation of struvite crystals ($NH_4MgPO_4 + 6H_2O$), of coffin-like forms, is very characteristic and takes place from very dilute solutions (rendered alkaline) on the addition of a grain of salt of phosphorous or a drop of sodium phosphate.

Iron. From hydrofluosilicic solutions, crystals of $FeSiFl_6 + 6H_2O$, which are isomorphous with those of magnesium salts, with the same optical characters. They may be differentiated by moistening with potassium ferrocyanide or ammonium sulphide, in the first case by turning blue, in the second case black.

Aluminium. From hydrofluosilicic solutions, not satisfactory on account of the gelatinous formation.

Behrens' Method.† (Hydrofluoric and Sulphuric Acids.)

This method depends on common reactions that can be made rapidly, but has the disadvantage of being rather complicated and requiring delicate manipulation.

The tests are best made upon about ½ mg. of powder with HFl (pure and fuming). As soon as the fluorides begin to dry treat with dilute H_2SO_4 and warm until white fumes of SO_3 appear. In this way the HFl and $SiFl_4$ are driven off and the sulphates are left. This part of the test can conveniently be made on a piece of platinum foil. Add excess of water and concentrate.

Transfer a drop to a clean object glass and, while still liquid, examine it with the microscope. Do not use a cover-glass over the drop.

Crystallizations Obtained by Behrens' Method.

Potassium. Add a little platinic chloride when octahedral crystals of K_2PtCl_6 (size .18 to .30 mm.) will appear, which are clear bright yellow in color with strong refraction.

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* After Lévy and Lacroix.

† *Natuurkunde*, Amsterdam, 2, Vol. XVII., 1881. *Chemical News*, Vol. LXIII., No. 1647, June, 1891, et seq.

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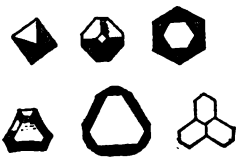

FIG. 45.—Potassium platinic chloride.*

Sodium. Use sulphate of cerium and allow a small amount of this reagent to act through a capillary pipette upon a drop of the solution. Very small aggregates of brown crystals (size .02 mm.) of the double sulphate of cerium and sodium are formed, which are clearly visible with 600 diams. If potassium is present the double sulphate of that alkali will appear in larger, grayish grains (size .05 to .06 mm.). An excess of H_2SO_4 is to be avoided.

Calcium. After a few minutes little gypsum crystals ($CaSO_4 + 2H_2O$) will appear. In strongly acid solutions the thin acicular crystals will be grouped in bushes or stars; in neutral solutions the crystals will have the normal shape of selenite crystals or form swallow-tailed twins.

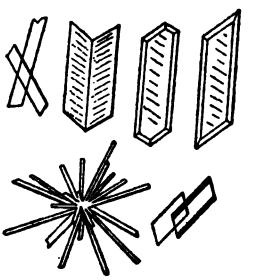

FIG. 46. — Sulphate of calcium (gypsum).*

Magnesium. Use salt of phosphorus dissolved in water and allowit to mix with the solution (to which has been added ammonium chloride and ammonia) through a capillary pipette. From a solution containing more than 5 per cent. of magnesium are first deposited X-shaped skeletons and rudimentary crystals of $Mg.NH_4.PO_4+6H_2O$. If the solution is more dilute beautiful, sharp, hemi-morphic crystals (.10 to .20 mm. in size) of the orthorhombic system will appear. These crystals often resemble the roof of a house. The formation of the crystals is assisted by heat. Iron and manganese phosphates yield crystals of the same type, but the iron is separated on the addition of ammonia.

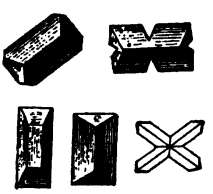

FIG. 47.—Magnesium ammonium phosphate.*

Aluminium. Use chloride of caesium. Take a drop of the so lution, with excess of H_2SO_4 driven off, and touch it with a platinum wire that has been dipped in the melted chloride of cæsium. Large crystals (.40–.90 mm. in size) of cæsium alum will form, which are octahedral and cubo-octa-

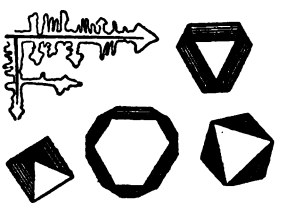

FIG. 48.—Cæsium alum.*

* After Lévy and Lacroix.

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hedral in shape. Iron does not interfere as its crystallization would take place much more slowly. The solution should not be too concentrated.

Special Tests.

Distinction between haüynite (contains $CaSO_4$) and noselite (contains Na_2SO_4). Treat with HCl and on evaporation the characteristic crystals of gypsum will be seen if the mineral is haüynite. Dilute acid should be used and as low a temperature maintained as possible, otherwise crystals of anhydrite would form instead of gypsum.

Recognition of apatite by test for phosphorus. Treat with a drop of ammonium molybdate dissolved in HNO_3. After complete action remove the solution to a clean object glass, when after slight warming a large number of very small yellow crystals (rhombic dodecahedral in shape) will form. The test may be used to distinguish this mineral from nephelite, melelite and natrolite. In the presence of soluble silica evaporate to render it insoluble and treat again with HNO_3 and the reagent.

Other micro-chemical tests are not mentioned for the reason that in elaborate chemical investigations of sections or isolated fragments resource should be made to the most complete publications on the subject.

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APPENDIX.

Brief Scheme of Classification into Systems by Optical Determinations.

HOMOGENEOUS. The whole substance shows the same optical character, except in the case of twin crystals when the different portions of the twin are affected differently.

Isotropic . . . . . All sections of the substance remain dark during a complete rotation between crossed nicols, and no interference figure is produced by convergent light.

Amorphous . . . Absence of crystalline form or cleavage.

Isometric . . . . Presence of crystalline form or cleavage.

Anisotropic . . . . Sections generally show some interference color and extinguish four times, at 90° apart, during complete rotation.

Uniaxial . . . . . Determined by character of interference figures obtained by convergent light from sections which remain dark or nearly so during complete rotation.

All sections show symmetrical extinction.

Tetragonal . . . . Sections giving interference figures are four- or eight-sided, or show rectangular cleavage.

Hexagonal . . . . Sections giving interference figures are three-, six- or nine-sided, or show cleavage lines intersecting at 60°.

Biaxial. . . . . . Determined by character of interference figures obtained by convergent light.

Orthorhombic . . Symmetrical extinction in all sections.

Monoclinic. . . . Symmetrical extinction only in the ortho zone 0 P : ∞ P$\bar{\infty}$ (001 : 100); all other sections show extinction angles.

Triclinic. . . . . Extinction angles in all sections, although in some minerals these extinction angles may be very small.

AGGREGATE . . Not homogeneous, but made up of an aggregation of individuals, all extinguishing at different times.

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METHOD OF MEASURING THE STRENGTH OF THE DOUBLE REFRACTION BY VON FEDEROW MICA WEDGE.*

"The wedge† consists of fifteen superposed quarter undulation mica plates, each about two mm. shorter than the one beneath it and with their axes of elasticity parallel. The series is mounted on a strip of glass and covered with a cover glass.

The wave-length of a middle color may be taken as 560 $\mu\mu$ (millionths of a millimeter); hence each quarter undulation mica plate may be considered to possess a phase difference or retardation of 140 $\mu\mu$. If, then, between the polarizer and analyzer we insert the mica wedge, so that its axis of least elasticity is at right angles to that of a mineral under examination, we substract from the phase difference of the mineral an amount equal to n times 140 $\mu\mu$, in which n represents the number of superposed mica plates in the field. When the mineral appears dark the value evidently corresponds closely to the phase difference of the mineral.

From the expression $\Delta = e X.$, in which Δ is the phase difference or retardation, X the double refraction, and e the thickness in millionths of millimeters, the thickness can be deduced when the double refraction is known or *vice versa*. If a mineral of known double refraction can be found in the section near the mineral under investigation,‡ the double refraction of the latter can be deduced by measuring the phase difference of the known mineral, whence e results and this substituted in the above formula yields X."

The colors produced between crossed nicols are:

No. of Micas interposed.	Color Produced.	Order.	No. of Micas interposed	Color Produced.	Order.
1	gray	first	9	indigo	third.
2	bright	"	10	emerald green	"
3	orange yellow	"	11	citron yellow	"
4	orange red	"	12	orange	"
5	violet blue	second	13	violet	fourth.
6	green	"	14	grass green	"
7	greenish yellow	"	15	greenish yellow	"
8	orange	"			

* A. J. Moses, *Trans. N. Y. Acad. Sci.*, Vol. XVI., p. 55, Jan., 1897.

† E. von Federow, *Zeit. f. Kryst, etc.*, Vol. XXV., p. 340, 1895.

‡ It is not safe to use minerals near the edge of the section, as the thicknesses are apt to be unequal.

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Example. In a thin section of fine grained granite a grain of quartz was selected and the section rotated between crossed nicols until its maximum interference color was obtained.* The color was a bright gray of the first order and, upon introducing the mica wedge, it was found that one thickness ($n = 1$) of mica reduced the color to black; therefore the phase difference was 140 $\mu\mu$. The double refraction of quartz (X) is known to be 0.009; hence from the formular $\Delta = eX$ we have $e = 15000\,\mu\mu = 0.015$ *mm.* (a very thin section).

The section of mica, whose double refraction was to be determined, was now rotated until its maximum interference color was obtained. The color was a bright reddish blue (lower second order), which required four ($n = 4$) thicknesses of the mica wedge to reduce to black.† Hence, $\Delta = 4 \times 140 = 560$ (more accurately by color chart 640). From formula $\Delta = eX$ we have $X = 0.042$, which is the double refraction of muscovite. Thus if the mineral is not recognized in other ways a knowledge of its approximate double refraction may greatly aid in its determination.

Order of Consolidation of the Constituent Minerals in Plutonic Rocks.

"There is in plutonic rocks a normal order of consolidation for the several constituents, which holds good with a high degree of generality. It is in the main, as pointed out by Rosenbusch, a law of 'decreasing basicity.' The order is briefly as follows:

1. Minor accessories (apatite, zircon, sphene, garnet, etc.) and iron ores.

2. Ferro-magnesian minerals—olivine, rhombic pyroxenes, augite, ægirine, hornblende, biotite, muscovite.

3. Felspathic minerals—plagioclase felspars (in order from anorthite to albite), orthoclase (and anorthoclase).

4. Quartz, and finally microcline.

In most rocks such minerals as are present follow the above order. The most important exceptions are the intergrowth of

* The grain selected should always be that, of the several grains present of the same mineral, giving the highest order interference color.

† After the first rough determination of the phase difference by the mica wedge, the more exact phase difference can be obtained by the aid of a good color chart, see p. 23. For example $4 \times 140 = 560$, but by the color chart it is seen that 640 more exactly expresses the phase difference.

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orthoclase and quartz and the crystallization of quartz in advance of orthoclase in some acid rocks, and the rather variable relations between groups 2 and 3 in some more basic rocks. The order laid down applies in general to parallel intergrowths of allied minerals; thus when augite is intergrown with ægirine or hornblende the former mineral forms the kernel of the complex crystal and the latter the outer shell; when a plagioclase crystal consists of successive layers of different compositions the layers become progressively more acid from the centre to the margin.

Certain constituents having variable relations are omitted from the foregoing list. Thus nepheline (elæolite) and sodalite belong to group 3, but may crystallize out either before or after the felspars."*

* Harker, *Petrology for Students*, p. 28, 1895.

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NEWTON'S COLOR-SCALE, ACCORDING TO QUINCKE.*

No.	Retardation in Millionths of Millimeters.	Interference Color† between Crossed Nicols.	
1	0	Black.	First Order.
2	40	Iron-gray.	
3	97	Lavender-gray.	
4	158	Grayish blue.	
5	218	Clearer gray.	
6	234	Greenish white.	
7	259	Almost pure white.	
8	267	Yellowish white.	
9	275	Pale straw-yellow.	
10	281	Straw-yellow.	
11	306	Light yellow.	
12	332	Bright yellow.	
13	430	Brownish yellow.	
14	505	Reddish orange.	
15	536	Red.	
16	551	Deep red.	
17	565	Purple.	Second Order.
18	575	Violet.	
19	589	Indigo.	
20	664	Blue (sky-blue).	
21	728	Greenish blue.	
22	747	Green.	
23	826	Lighter green.	
24	843	Yellowish green.	
25	866	Greenish yellow.	
26	910	Pure yellow.	
27	948	Orange.	
28	998	Bright orange-red.	
29	1101	Dark violet-red.	
30	1128	Light bluish violet.	Third Order.
31	1151	Indigo.	
32	1258	Greenish blue.	
33	1334	Sea-green.	
34	1376	Brilliant green.	
35	1426	Greenish yellow.	
36	1495	Flesh-color.	
37	1534	Carmine-red.	
38	1621	Dull purple.	
39	1652	Violet-gray.	Fourth Order.
40	1682	Grayish blue.	
41	1711	Dull sea-green.	
42	1744	Bluish green.	
43	1811	Light green.	
44	1927	Light greenish gray.	
45	2007	Whitish gray.	

* Ueber Newton'sche Farbenringe und totale Reflexion des Lichtes bei Metallen, *Pogg. Ann.*, 1866, cxxix, 177.

† The terms *low* and *high* are used to describe the relative positions of the interference colors in the scale; *low* referring to the 1st order colors at the beginning of the scale, and *high* to the 3d and 4th order colors towards the end of the scale.

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OPTICAL SCHEME.

Introduction.

The scheme is designed to put before the student a short, practical way of recognizing the common minerals in rock sections.

The arrangement followed has been to group minerals having general optical characters in common, at the same time giving their specific characters so as to make their differentiation possible.

A mere tabulation of the minerals, with a list of optical characters appended, may be of aid to the skilled investigator, but is of very little assistance to the beginner.

The more common minerals, or those which are important petrographically, are printed in heavy-faced type; the minerals of less importance in small capitals.

Abbreviations and Conventions Used.

A. = Amorphous.
I. = Isometric system.
T. = Tetragonal system.
O. = Orthorhombic system.
M. = Monoclinic system.
Tri. = Triclinic system.
H. = Hexagonal system.
M(H). = Monoclinic, with hexagonal form or characters, as in the case of biotite.
$\perp$ = At right angles to.
El. = Elongation.*
Ex. = Extinction.
|| Ex. = Parallel extinction, as when the crystals extinguish parallel to cleavage lines or edges. Extinction which is symmetrical to intersecting cleavage lines is also included under this term.

The term "grains" is used to describe not only minerals which occur in typically granular form, but also those which have coarser allotriomorphic form, as elæolite and sodalite in plutonic rocks, such as syenite, etc.

* In crystals of long prismatic habit marked elongation would show that the section was taken approximately parallel to the vertical or prism axis. In crystals of tabular habit (the micas) marked elongation would show that the section was approximately at right angles to the tabular faces (the basal faces in micas).

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GENERAL RULES FOR USE OF SCHEME,

In each rectangle the minerals are arranged in order of their indices of refraction, those being put at the top which have the smallest index and show the lowest *relief*.

The presence or absence of *relief* is based on the way the isolated mineral appears in Canada balsam. The case may arise, however, when a mineral of high index of refraction is surrounded by minerals of only slightly lower indices of refraction; the dark border or contour would then not be distinct, but the rough appearance of the surface would still remain.

Knowing the mineral species (and therefore their indices of refraction) surrounding the mineral section to be determined, the relative index of the latter can easily be obtained by applying Becke's method: Focus sharply on the line of contact between the known and unknown minerals;* then raise the objective slightly and the dark boundary will appear to move toward the mineral having the higher index of refraction.

When suitable conditions make the determination possible the approximate index of refraction of a thin crystal section can be obtained with the microscope by the Duc de Chaulnes' or Sorby's method.†

If the microscope is provided with an iris-diaphragm, the method of C. Viola ‡ can be used for the determination of the index of refraction. The method depends on the principle that the difference between the indices of refraction of two minerals in contact is directly proportional to the square of the opening in iris-diaphragm necessary to show the "bright line" most distinctly.

Care must be taken in making use of the horizontal divisions of the scheme, based on the strength of the *double refraction* and the resulting *interference colors*.§ The minerals are grouped according to the interference colors given by sections of the average thickness of 0.03 mm.||

* Have the convergent lens or condenser lowered and the analyzer out during this test.

† A. J. Moses, *Characters of Crystals*, p. 120.

‡ Abst. in *Bull. Soc. Franc. de Min.*, Vol. XIX., p. 131, 1896.

§ The colors vary with the thickness of the section and also with the orientation of the section in the crystal.

|| These sections are furthermore supposed to be those producing the strongest double refraction of light and giving the highest interference colors. That is, they are supposed to be parallel to the plane containing the maximum and minimum axes of elasticity a and c.

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When some known, or easily recognized, mineral in a given section shows an interference color indicating a thinner or thicker section* allowance must be made for a similar decrease or increase in the interference colors given by all the other minerals.

The lower and middle colors of the 1st order, from bluish-gray through white to yellow, are easily recognized. The bright red, blue, green, etc., colors of the 1st, 2d and 3d orders can also be differentiated without much trouble from the very high order colors (4th and above), which show no decided tint, but are rather neutral in tone.

Confusion might come in, however, in distinguishing at sight between the red of the 1st order and the red of the 2d order. The following simple test could then be made: Take a test-plate, giving red of the 1st order, and introduce it between the section and the analyzer, so that its axes of elasticity are parallel to the directions of elasticity in the section to be investigated.† When the test-plate is introduced so that dissimilar axes are superposed over those in the section the effect is to thin the section, and its interference color drops in the color scale.‡ The difference in phase of the test-plate is just about enough to drop or lower the color of the section through an order. Hence, if the section had previously shown red of the 1st order, the color appearing, after the introduction of the test-plate, would be a dark gray or black. If, on the contrary, the colors had been those of the upper 2d or lower 3d orders the effect of the test-plate would be to still show some bright color.

A quarter-undulation mica plate may also be conveniently used to distinguish a yellow of the 1st order from a yellow of the 2d order. If the plate be introduced in the manner just described, the effect is to lower the color a quarter undulation. Hence, the yellow of the 1st order would change to white, while the yellow of the 2d order would change to green.

In connection with the very high order interference colors, which show no decided tint (for example, the interference colors of titanite), it must be remembered that nearly all the rock-forming

* For instance, it would not be at all strange to find quartz, in a section thicker than the average, giving the bright red of the 1st order.

† The directions of elasticity of the section must, of course, lie at 45° to the planes of vibration of the crossed nicols in order to get the maximum interference color.

‡ When the test-plate is introduced in the opposite way the effect is to thicken the section and the interference color will rise in the scale.

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minerals, having strong double refraction, have also a high refractive index; the effect of which is to give a very bright or brilliant illumination to the surface of the section, which is quite independent of the interference colors. Calcite, which has not a very high refractive index, would be an exception to this rule.

The interference figures in convergent light increase in clearness and distinctness with the strength of the double refraction. In uniaxial crystals sections normal to the optic axis, *i. e.*, sections which remain dark during a revolution between crossed nicols, show the best interference figures. In biaxial crystals the most characteristic interference figures are shown by sections normal to the acute bisectrix.

Crystal sections which are too small do not give very satisfactory interference figures with convergent light.*

* In Seibert microscope, with No. V. objective, the results are unsatisfactory unless the crystal section takes up more than $\frac{1}{5}$ or $\frac{1}{4}$ of the field of view.

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shaped crystals or grains. Relief very high. Crystals

		Pleochroism or Absorption.		Not very transparent, brownish to yellowish, wedge-shaped crystals or grains. Relief very high. Crystals may be twinned. The very light colored grains show no pleochroism. May be no complete extinction in white light. Ex. angles not characteristic.
	DOUBLE REFRACTION Very Strong, ($\gamma - \alpha > 0.050$.) giving INTERFERENCE COLORS higher than 3d Order. The colors have no very decided tint.	No marked Pleochroism or Absorption.	**H. Calcite (—).** Colorless grains. Cleavage ‖ R. Interference colors *very* high order. Often shows polysynthetic twinning.	**H. Dolomite (—).** Like Calcite, but chiefly in crystals or with crystalline boundaries. The relief not very marked. **T. Zircon (+). El. ‖ c′.** Almost colorless, small, short, prismatic crystals. Very high relief. ‖ Ex. When included in other minerals, often surrounded by halo. **T. Rutile (+). El. ‖ c′.** Yellowish to reddish, minute, slender prisms or grains. Grains may be almost opaque and metallic. Geniculated twins very common. Very high relief.

AGGREGATES

Serpentine, Greenish color.
Chlorite, Greenish color, usually pleochroic.
} Very low order interference colors

Kaolinite, (clay). Cloudy and scarcely translucent. No change observed between crossed nicols.

* May show Optical Anomalies. † Interference colors often masked by strong absorption.

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INDEX.

MINERAL NAMES IN HEAVY-FACED TYPE.

Abbreviations, ... vii
Absorption, ... 19
Absorption tints, ... 15
Acmite, ... 60
Actinolite, ... 60
Acute bisectrix, ... 6
Ægirine, ... 60
Ægirine-augite, ... 60
Aggregate structure, ... 27
Albite, ... 74
Allotriomorphic, ... 13
Aluminium, test for, by Borichy's method, ... 100
test for, by Behren's method, . . 101
Amorphous bodies, ... 2
Amorphous substances, test for, . . 20
Amphibole, ... 60
Analcite, ... 57
Analyzer, ... 9
Andalusite, ... 51
Anhedron, ... 13
Anisotropic, ... 2
Anisotropic character, test for, . . . 20
Anomalies, optical, ... 20
Anorthite, ... 74
Anorthoclase, ... 78
Apatite, ... 47
Apatite, recognition of, by test for phosphorus, ... 102
Apparatus for petrographical laboratory, ... 91
Appendix, ... 103
Augite, ... 58
Axes of elasticity, ... 3
Axes of elasticity in a section, test for relative value of, ... 25
Axial angle, ... 6
Bastite, ... 54
Becke's method for determining index of refraction, ... 109
Behren's method. (Hydrofluoric and sulphuric acids), ... 100
Bertrand lens, ... 10
Biaxial crystals, ... 3, 4
Biaxial crystals, axes of elasticity in, . 4
Biaxial interference figures, ... 32
Biotite, ... 64
Bisectrix, acute, ... 6
Borichy's method. (Hydrofluosilicic acid), ... 98
Broken or strained crystals, ... 13
Bronzite, ... 54
Calcite, ... 45
Calcium, test for, by Borichy's method, 99
test for, by Behren's method, . . 101
Carbonaceous Matter, ... 43
Carbonaceous particles, test for, . . . 95
Carbonates, test for, ... 93
Cement, ... 86
Cementing, ... 86
Cement for mounting, ... 90
Centering stage, ... 9
Chalcedony, ... 45
Characters observed by, convergent light, ... 29
crossed nicols, ... 20
incident light, ... 11
polarized light, ... 18
Characters of opaque minerals, . . . 11
Characters of transparent minerals, . . 11
Chemical and mechanical tests, . . . 92
Chemical (micro) reactions, ... 98
Chemical separation, ... 97
Chemical tests on crystal in section, . 92
Chiastolite, ... 51
Chlorite, ... 67
Chromite, ... 36
Chrysolite, ... 55
Classification into systems by optical determinations, ... 103
Clay, ... 79
Cleaning and finishing, ... 91
Cleaning sections, ... 89, 90
Cleavage, ... 16

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Color, ... 15
Color-scale, Newton's, ... 107
Complete crystals, ... 11
Condensing lens, ... 8
Consolidation of minerals in plutonic rocks, order of, ... 105
Conventions, ... vii
Convergent light, ... 29
Convergent light, characters observed by, ... 29
Convergent and parallel light, résumé of uses of, ... 34
Cordierite, ... 56
Corroded crystals, ... 13
Corundum, ... 43
Crossed nicols, characters observed by, 20
Crossed twinning, ... 27
Crystallites, ... 14
Crystallizations obtained by Behren's method, ... 100
Borichy's method, ... 99
Cutting, ... 85
Cutting and grinding machines, . . . 82
Cyanite, ... 78
Damourite, ... 67
Delessite, ... 68
Diallage, ... 58
Diamond saws, ... 34
Dichroite, ... 56
Diopside, ... 58
Directions of elasticity in a section, test for relative value of, ... 25
Directions of elasticity or vibration, . . 3
Dispersion, ... 6
Disthene, ... 78
Dolomite, ... 47
Double image of a point, ... 2
Double refraction, ... 2
Double refraction, estimation of strength of, ... 22
strength of, measured by von Federow mica wedge, ... 104
Effects produced by crystals on transmitted light, ... 1
Elæolite, ... 49
Elasticity, axes of, ... 3
directions of, ... 3
Electric motor for grinding machine, . 82
Electro-magnetic separation, ... 97
Emery, grades of, for grinding, . . . 85, 87
Enstatite, ... 53
Epidote, ... 68
Etched figures, ... 93
Extinction, ... 23
angles, ... 23
tests for, ... 24
wavy, ... 24
Eye-pieces, ... 10
Fayalite, ... 56
Feldspar group, ... 71
Fibrolite, ... 52
Finishing and cleaning, ... 91
Focusing, ... 10
Form, ... 11
Fracture, ... 17
Garnet, ... 37
Gelatinizing silica, test for, ... 93
Glass slides, ... 90
Glaucophane, ... 63
Graphite, ... 42
Gridiron twinning, ... 27
Grinding, ... 87
and cutting machines, ... 82
apparatus for sections with parallel faces, ... 83
plates or laps, ... 85
Gypsum, ... 57
Gypsum test-plate, ... 25
Hardness of grains, ... 95
Haüyne, ... 39
Haüynite, ... 39
Haüynite and noselite, distinction between, ... 102
Heating sections to redness, ... 94
Heavy solutions, ... 96
Hematite, ... 43
Hexagonal crystals, ... 3
High relief, ... 15
Hornblende, ... 60
Hyalosiderite, ... 56
Hypersthene, ... 53
Hydrofluosilicic acid tests, ... 98
Idiomorphic, ... 11
Idocrase, ... 42
Ilmenite, ... 43
Incomplete crystals, ... 13
Index of refraction, ... vii, 25
by Becke's method, ... 109
by Sorby's " 109
by Viola's " 109

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Incident light, ... 11
characters observed by, ... 11
Inclusions, ... 18
Indicators for specific gravity separation, ... 96
Interference colors, ... 23
Interference figures, ... 29
biaxial, ... 32
uniaxial, ... 30
Interference colors, produced by mica wedge, ... 104
Interference color-scale, Newton's, . . 107
Iolite, ... 56
Iron, test for, by Borichy's method, . 100
test for, by Behren's method, 101
Isolating crystals or mineral fragments for testing, ... 95
Isometric crystals, ... 2
Isotropic, ... 2
Isotropic character, ... 20
Kaolinite, ... 79
Labradorite, ... 74
Laps for grinding, ... 85
Lepidolite, ... 67
Leucite, ... 38
Leucoxene, ... 43
Light, incident, ... 11
ordinary, ... 1
plane polarized, ... 1
Limonite, ... 35
Low relief, ... 15
Machines for cutting and grinding, . . 82
Magnesium, test for, by Borichy's method, ... 100
test for, by Behren's method, . . 101
Magnetic iron ore, ... 36
Magnetic pyrites, ... 35
Magnetite, ... 36
Measuring strength of double refraction by von Federow mica wedge, 104
Mechanical and chemical tests, . . . 92
Melilite, ... 42
Menaccanite, ... 43
Methods of preparing sections, ... 81
Mica group, ... 64
Mica plate (quarter undulation), . . . 25
Mica wedge, von Federow, ... 104
Micro-chemical reactions, ... 98
Microcline, ... 73
Microlites, ... 14
Microscope (petrographical), ... 7
Microscopic and optical characters of minerals, ... 11
Monoclinic crystals, ... 3
Monoclinic crystals, axes of elasticity in, ... 4
Monoclinic pyroxenes, ... 58
Motor, electric, for grinding machine, . 82
Mounting, ... 89
Mounting solutions, ... 90
Muscovite, ... 64
Natrolite, ... 57
Negative crystals, ... 18
Negative optical character, biaxial, . 33
uniaxial, ... 31
Nepheline, ... 49
Nephelite, ... 49
Newton's color-scale, ... 107
Nicol prism, ... 7
Nosean, ... 39
Noselite, ... 39
Noselite and haüynite, distinction between, ... 102
Nose-piece for microscope, ... 9
Objectives, ... 9
Oblique extinction, ... 24
Oligoclase, ... 74
Olivine, ... 55
Opal, ... 35
Opaque minerals, characters of, . . . 11
Optical, anomalies, ... 20
character, biaxial, ... 33
character, uniaxial, ... 31
and microscopic characters of minerals, ... 11
scheme, ... 108
principal section, ... 4
Optic axis, ... 3
Optics for optical mineralogy, ... 1
Order of consolidation of minerals in plutonic rocks, ... 105
Ordinary light, ... 1
Orthoclase, ... 71
Orthorhombic crystals, ... 3
axes of elasticity in, ... 4
Orthorhombic pyroxenes, ... 53
Parallel face sections, grinding apparatus for, ... 83
Parallel and convergent light, résumé of uses of, ... 34

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Perofskite, ... 39
Perovskite, ... 39
Petrographical, apparatus, ... 91
microscope, ... 7
Parallel extinction, ... 23
Phenochryst, ... 12
Phlogopite, ... 64
Picotite, ... 37
Piedmontite, ... 69
Plagioclases, ... 74
Plane polarized light, ... 1
Plates, grinding, ... 85
Pleochroism, ... 19
test for, ... 19
Pleonaste, ... 37
Polarized light, characters observed by, 18
plane, ... 1
Polarizer, ... 7
Polishing sections, ... 88
Polysynthetic twinning, ... 27
Positive optical character, biaxial, . . 33
uniaxial, ... 31
Potassium, test for by Borichy's method, 99
test for by Behren's method, . . 100
Preparation of sections, ... 81
Principal section, optical, ... 4
Principal vibration directions, ... 3
Prism, nicol, ... 7
Pseudomorphic structure, ... 28
Pyrite, ... 35
Pyrites, ... 35
Pyrrhotite, ... 35
Pyroxenes, orthorhombic, ... 53
Pyroxenes, monoclinic, ... 58
Quarter-undulation mica-plate, ... 25
Quartz, ... 44
test-plate, ... 25
wedge, ... 27
Refraction, double, ... 2
Relative value of the two directions or axes of elasticity in mineral section, test for, ... 25
Reflector, ... 7
Refraction, index of, ... vii, 15
Relief, ... 15
high and low, ... 15
test for, ... 16
Resorption border, ... 61
Résumé of uses of parallel and convergent light, ... 34
Rotating stage, ... 8
Rutile, ... 40
Sagenite, ... 40
Sanidine, ... 73
Saussurite, ... 78
Saws, ... 84
Scapolite Group, ... 41
Scheme of classification into systems by optical determinations, ... 103
Scheme, optical, ... 108
Schiller structure, ... 18
Sections, methods of preparing, . . . 81
thickness of, rock, ... 88
Separation, by specific gravity, ... 96
by electro-magnet, ... 97
by chemical means, ... 97
Serpentine, ... 79
Shagreened surface, ... 15
Shorl, ... 50
Sillimanite, ... 52
Simple twinning, ... 27
Single image of a point, ... 2
Skeleton crystals, ... 15
Slides, glass, ... 90
Sodalite, ... 39
Sodalite Group, ... 39
Sodium, test for, by Borichy's method, 99
test for, by Behren's method, . . 101
Sorby's method for determining index of refraction, ... 109
Special micro-chemical tests, ... 102
Specific gravity separation, indicators for, ... 96
Sphærulitic structure, ... 27
Sphene, ... 69
Spinel, ... 37
Stage, rotating, ... 8
Staurolite, ... 52
Stauroscopic methods, ... 25
Strained or broken crystals, ... 13
Strength of double refraction, measure of, ... 104
Structure, ... 27
Symmetrical extinction, ... 23
Systems, classifications into, by optical determinations, ... 103
Talc, ... 56
Tetragonal crystals, ... 3
Thickness of rock sections, ... 88
Titanite, ... 69

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Transmitted light, ... 11
effect on crystals, ... 1
Transparent minerals, characters of, . 11
Tremolite, ... 60
Triclinic crystals, ... 3, 5
axes of elasticity in, ... 5
Tridymite, ... 45
Topaz, ... 52
Tourmaline, ... 50
Twinning, ... 27
Uniaxial crystals, axes of elasticity in, 3
Uniaxial interference figures, ... 30
Uralite, ... 63
Uralitization, ... 64
Uses of parallel and convergent light, 34
Vesuvianite, ... 42
Vibration, direction of, ... 3
plane of nicol, ... 8
Viola's method for determining index of refraction, ... 109
von Federow mica wedge, ... 104
Wavy extinction, ... 24
Wedge, mica, ... 104
quartz, ... 27
Wernerite, ... 41
Zeolites, ... 57
Zircon, ... 40
Zoisite, ... 69
Zonal structure, ... 27

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